Integrated Operations Architecture Technology Assessment Study

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EXECUTIVE SUMMARY

As part of NASA's Integrated Operations Architecture (IOA) Baseline, NASA will consolidate all communications operations, including ground-based, near-earth, and deep-space communications, into a single integrated network. This network will make maximum use of commercial services and standards. It will be an Internet Protocol (IP) based network.

This study, prepared by Science Applications International Corporation, supports technology development planning for the IOA. The technical problems that may arise when LEO mission spacecraft interoperate with commercial satellite services were investigated. Commercial technology and services that could support the IOA were surveyed, and gaps in the capability of existing technology and techniques were identified. Recommendations on which gaps should be closed by means of NASA development funding were made.

Several findings emerged from the interoperability assessment:

- In the NASA mission set there is a preponderance of small, inexpensive, low data rate science missions, and this trend is likely to continue, given NASA's commitment to low-cost access to space and the widespread interest in microsats.

- A commercial satellite communications service could provide TDRSS-like data relay functions.

- IP and related protocols such as TCP require augmentation to operate in the mobile networking environment required by the space-to-ground portion of the IOA.

In the technology assessment, five case studies were performed. Each case represents a realistic implementation of the near-earth portion of the IOA. The cases represented frequencies at L-band, Ka-band, and the optical spectrum. The cases also represented both space relay architectures and direct-to-ground architectures. The main findings include:

- Low cost COTS technology from Spaceway and Astrolink will soon be available to implement a commercially operated Ka-band "VSAT-like" direct-to-ground network.

- At least two companies, Universal Space Network and Allied Signal, are prepared to provide turnkey communications service for LEO spacecraft. Depending on the level of customer commitment, they would be able to upgrade to Ka band.

- A number of companies including Deskin Research, Swedish Space Corporation, and Datron build small earth terminals for serving LEO spacecraft, capable of operating at S, X, and Ka band.

- Spacehab, Inc., is in the process of developing a space-qualified transceiver for interfacing with Inmarsat's global MSS network to provide real-time low data rate command and telemetry service.

Some of the main recommendations resulting from the case studies are:

- Select an architecture for the LEO/MEO communications network.

- Pursue the development of a Ka-band space-qualified transmitter (and possibly a receiver), and a low-cost Ka-band ground terminal for a direct-to-ground network.

- Pursue the development of an Inmarsat (L-band) space-qualified transceiver to implement a global, low data rate network for LEO/MEO mission spacecraft.

- Pursue developmental research for a miniaturized, high data rate optical transceiver.

1. INTRODUCTION

1.1 Background

National Space Policy directs NASA to begin a transition to commercially provided communications services. The emergence and rapid growth of advanced terrestrial telecommunications, wireless services, and the Internet offer opportunities for NASA to leverage these significant commercial accomplishments. The Integrated Operations Architecture (IOA) envisioned in the recent $3.4 billion Consolidated Space Operations Contract (CSOC) capitalizes on that observation and is recognized as the foundation for NASA's future space services. The primary goal of the IOA is to achieve cost reduction through consolidation of all operations and the maximum use of commercial services and products. To help achieve these objectives it was decided to standardize the IP and associated protocols throughout the network. In this report we will refer to the NASA-internal private network as the NASA IOA Intranet, or simply, the intranet.

There are significant gaps in the currently available technologies that will be required to fully enable the IOA vision of a Solar System Area Network, where every spacecraft and instrument becomes a node. The purpose of the study is to identify those gaps and provide a rational plan for their closure. As part of the objective of achieving a globally integrated IP intranet, first NASA's heterogeneous ground networks must be consolidated, followed by or paralleled by a phased absorption of the space-to-ground communications networks into the same intranet. This study focuses on the space-to-ground portion of this intranet. The IOA plan envisions that the first phase of integration will consist of NASA ground stations becoming IP-addressable within the NASA intranet. The second phase will be for NASA science mission spacecraft to be IP-addressable from ground stations. The third and final phase will be for NASA spacecraft to be IP-addressable from other NASA spacecraft [CSOC].

This study, prepared by Science Applications International Corporation, investigates the readiness of commercial network services and communications technologies to support the needs of NASA in near-earth to near-planetary missions over the next ten to fifteen years. Its ultimate purpose is to identify critical gaps in technology, where modest investments in applied research and low level proof-of-concept development in communications and networks technologies can make significant long-term impact on the way NASA Enterprises conduct their space missions. Technologies and techniques will be required to "close the gaps" to enable NASA to interoperate with commercially provided assets.

The need for such a study is evidenced by several factors. The increase in number and frequency of space missions proposed by the Enterprises is expected to continue. Some will have collections of sophisticated instruments working in tandem, while others will fly in formations and constellations to accomplish their scientific mission. As spacecraft become more autonomous and capable, it is anticipated that NASA's aggregate telecommunications requirement will be in danger of exceeding the available and projected NASA resources.

1.2 General Observations

Recognizing the rapid growth in technology for commercial satellite telecommunications, NASA and NSF have sponsored several detailed systems and technology reviews over the past few years. The most recent one was conducted by the World Technology Evaluation Center

(WTEC). According to this study, commercial communications satellite services are rapidly becoming a large and global business, increasing from $11 billion in 1992, to $20 billion in 1996, to a projected figure of $75 billion in 2005. The United States is apparently leading the way in proposals for new services and new satellites and in the innovative financing of new ventures to provide these services.

New technology is being inserted into commercial satellite communications at an increasingly rapid pace. Recent examples include onboard processing and switching, more efficient solar cells, higher power components, more efficient heat dissipation techniques, electric-based station keeping thrusters, intersatellite links, large antennas, phased array antennas, multiple spot beam antennas, and improved TWTAs.

While U.S. manufacturers are developing short-term, or competitive, technologies, it appears that longer term work is being neglected. WTEC identified several possible candidates for long-term U.S. government supported R&D that will enable U.S. industry to maintain its lead in the development and manufacture of the commercial communications satellites of the future. They include:

- Batteries and fuel cells

- High power components and structural elements

- Materials and structures for numerous electronic devices, including solar cells and high frequency devices (>20 GHz)

- Materials that are light in weight and strong for structural applications

- Devices and structures for phased array and multiple spot beam antennas for use on the ground and in space

- Radiation resistant device structures and circuits

- Techniques, materials, and structures for the transfer and dissipation of heat

- Optical components and sub-systems

- Networking technology for the seamless integration of high data rate communication satellites and terrestrial facilities

- Large, deployable antennas (>25 meters in diameter)

Further, future development of commercial satellite communications appears to hinge on key regulatory and standards issues as much as new technology development. Perhaps most critical is the need for interoperability standards to seamlessly connect new satellites with terrestrial networks for public telephony, wide-band services, and many forms of Internet access and commercial systems. This implies world wide government leadership in the promotion of standards, as well as technology development.

1.3 Study Methodology

The IOA Baseline [CSOC] is a primary input to the study as the reference for NASA policy and future directions. NASA missions are surveyed in order to estimate realistic bounds for the communications requirements. Commercial services that may meet the mission requirements are

compiled and described. These services are then analyzed to identify potential problem areas that may arise if they are to be interfaced to NASA mission spacecraft. Problem areas examined include ITU regulations, radio frequency usage, coverage, link access, and protocol problems. Next, the interoperability problems and technology issues are assessed in the context of five realistic network architectures ("cases"). The specific problem areas and "gaps" are identified for each case. Finally, the results of the technology assessment are used as a basis for making specific recommendations on technical problems and technologies that NASA should devote resources to, in support of the IOA.

1.4 Assumptions

The following major assumptions have been made:

- Only the space-to-ground communications network will be addressed, not the terrestrial network
- The network will be operated by a commercial service provider
- Only near-earth orbiting NASA science missions will be included
- IP will be used as the Internet routing protocol
- The mission spacecraft will be IP-addressable
- NASA spacecraft act like standard users to commercial providers
- All NASA spacecraft will transition to Ka band at some future date
- Only technologies specific to the IOA will be investigated
- Use of COTS and modified COTS items will be maximized

2. NASA MISSION SURVEY

The goals identified in NASA's Strategic Plan will be achieved through an Enterprise Organization, composed of the Space Science Enterprise, Earth Science Enterprise, Human Exploration and Development of Space Enterprise, and the Aero-Space Technology Enterprise. Integral in achieving these goals is a diverse series of missions, involving currently operational, planned, and future spacecraft.

Each of these missions has been either assigned to or developed within a particular enterprise. Thus, from an operational perspective, NASA has formally grouped the set of missions and supporting spacecraft. A goal in this study is to "ungroup" these missions and view them from a purely communications requirements perspective. This communications perspective consists of forming a communications parameter set, developing a measurable scale for each parameter, sorting the mission set by each of these parameters and metrics, and analyzing the results.

This will result in a multi-dimensional communications analysis of current, planned, and future NASA missions that would be a critical piece of information when planning upgrades and/or the replacement of existing NASA communications services.

This section is divided into subsections addressing the Selection Criteria, Parameter Set, Mission Classification, and Analysis. The Selection Criteria subsection addresses how a base set of fifty-one NASA missions was selected. The Parameter Set subsection discusses the rationale and identifies the technical parameters used to develop mission classification. An Analysis Results subsection highlights some of the findings derived from the mission type groupings.

2.1 Mission Selection Criteria

To develop a base set of missions for this study, exclusionary criteria were applied to NASA Enterprise missions. These criteria, discussed in the subparagraphs below, range from "temporal scope" to those of NASA's roles and responsibility.

2.1.1 Time Frame

The temporal scope of this study is ten years. Missions not meeting this basic criterion were dropped from consideration. Closely related is the criterion that missions currently identified as a "Mission in Operation" in the *Mission Requirements and Data Systems Support Forecast* document (produced by NASA's Network and Mission Services Office) must not exceed their planned operational lifetime. Missions satisfying the following formula were dropped from consideration:

$$(1999 - \text{Launch Date}) \geq \text{Project Lifetime}[1]$$

These missions are listed in the following table:

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[1] As defined in *Mission Requirements and Data Systems Support Forecast*, Updated 4 June 1999, Network and Mission Services Office, Code 450.

Mission	Launch Date (Month Year)	Project Lifetime (Years)
Galileo	Oct 89	10
ROSAT	Jun 90	8
Compton Gamma Ray Observatory (GRO)	Apr 91	8
Extreme Ultraviolet Explorer (EUVE)	Jun 92	7
GEOTAIL	Jul 92	6
TOPEX	Aug 92	4
WIND	Nov 94	4
SURFSAT-1	Nov 95	3
SOHO	Dec 95	3
POLAR	Feb 96	2
Mars Pathfinder (Discovery-2)	Dec 96	2
Advanced Composition Explorer (ACE)	Aug 97	2
Engineering Test Satellite (ETS-VII)	Nov 97	1.5
SNOE (Student Nitric Oxide Experiment)	Feb 98	1

There were exceptions (noted in the table below) made to the above exclusionary formula. These exceptions were made because they represent missions that are operational and represent an operational mission class that has a high probability of continued implementation and launches. This direction is evidenced in NASA's current budget and strategic direction. For example, the percentage of NASA's budget devoted to human spaceflight has declined from 48% in FY91 to 40% currently and is projected to decline to 35% by FY04. In the early 1990s, the average cost of spacecraft development was $590 million. NASA's goal for FY00 to FY04 is $79 million. NASA's annual flight rate is projected to grow from two in the early 1990s to 14 flights per year (on average) from FY00 to FY04.[2] The exceptions were:

Mission	Launch Date (Month Year)	Project Lifetime (Years)
FAST (SMEX-2)	Aug 96	2
SAMPEX (SMEX-1)	Jul 92	6
TRACE (SMEX-4)	Apr 98	1

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[2] Statement of Daniel S. Goldin, Administrator of NASA, before the Subcommittee on VA-HUD-Independent Agencies Committee on Appropriations, U.S. Senate, 18 March 1999.

Another basic criterion is that instrumentation platforms must be "spaceborne." Thus, missions flown aboard aircraft or balloons were not included. NASA systems not included in this study were:

- Satellite Telemetry and Return Link (STARLINK): This is a real-time airborne science and disaster assessment system on board the Lockheed ER-2.

- Remote Aircraft Satellite Communication Link (RASCL): This is an on-going high altitude, unmanned aircraft used for data gathering.

- Long Duration Balloon Programs (LDBP): These are experiments put upon a balloon platform to reach and research the uppermost limits of the earth's atmosphere.

Another exclusionary criterion is that selected missions be those in which NASA had a continuing operational responsibility, such as a primary operator, communications provider, or backup. This excluded the mission National Oceanic and Atmospheric Administration–15 (NOAA-15). For this mission, NASA has only Launch and/or Early Orbit responsibility.

It should be mentioned that NASA's responsibilities for the Geostationary Operational Environmental Satellites (GOES) J, K, L, and M satellites do not include on-orbit operations. NOAA will perform this role. However, NASA is tasked via an Memorandum of Agreement with NOAA to provide backup capability for GOES telemetry and commanding. Thus, GOES vehicles are included in the study.

The entire list of 51 satellites considered for this study is listed in Appendix A.

2.2 Mission Classification Parameters Set

In order to group spacecraft missions into sets, parsed by communications related parameters, a set of measurable parameters was required. Several factors influenced parameter selection. These ranged from data availability to being either directly related to or derivable from communications requirements.

A significant driver in parameter selection was data availability. To partition missions using a parameter set, each mission must have data defined for each parameter. This kept the parameter set "granularity" to a first order of magnitude, in that when an attempt was made to include parameters of a more detailed nature (e.g., spacecraft antennae characteristics), it was found that data were not uniformly available among the mission set. Thus, included parameters were those for which spacecraft data were available or could be extrapolated from a similar mission. Missions lacking parameter information and therefore excluded from the study included:

Mission	Program or Enterprise
CloudSat	ESSP
VOLCAM	ESSP
Picasso-Cena	ESSP
MIDEX 3,4,5,6	Explorers
GALEX	Explorers
ACRIMSAT	EOS

Another criterion is that the parameters must be directly related to or have a derived relationship with satellite communications requirements. Of those selected, several have an obvious and direct relationship. These include the uplink and downlink frequencies, uplink and downlink data rates, and TDRSS use.

Other parameters can be viewed as having a derivative impact either through link budgeting equations or in determining the quantity of earth stations. The chosen parameter set is defined by the following elements:

- Satellite Quantity
- Orbital Altitude (Perigee and Apogee)
- Orbital Inclination
- Uplink Frequency
- Downlink Frequency
- Uplink Data Rate
- Downlink Data Rate
- On Board Solid State Memory (Presence and Size)
- TDRSS Usage

2.3 Mission Classification

Mission classification involved partitioning (if required) each of the parameter set elements into a range of values. For some parameters, this was trivial because of an existing natural partitioning. Examples of this include the uplink and downlink frequencies. Data provided via web sites and other resources often identified the various frequency bands (S, X, Ka, Ku, etc.) used by the satellite's communications subsystem. Other parameter partitions required a judgment call, particularly the data rate and orbital altitude elements. These partitions are identified in the charts below.

Although the element partitions (see analysis section) are well defined, the reasoning in selecting one particular partitioning precision over another (e.g., data rates) was not arbitrary. Partitioning data rate elements could have used a standard bandwidth division schema (e.g., T-1 and OC-1). We believe that this would have grouped too many elements into one large partition. So, partitions were made in a non-standard way, allowing the reader better visibility into the makeup of each partition.

2.4 Analysis

This section identifies the parameter partitioning used to sort the mission spacecraft and discuss results.

2.4.1 Uplink Data Rates

The uplink data rates that comprise the chart below were obtained from a table (see Appendix A) where for each spacecraft, a single uplink maximum data rate was identified and parsed. Perhaps most striking about the uplink data rates graph below are the extremely low data rates involved. Clearly, 89% of the uplink data rates do not exceed 2 Kbps, and of the small proportion of data rates exceeding 2 Kbps, the highest data rate is 19.2 Kbps.

Uplink Data Rates (Kbps)

2 < x
11%

0 < x <= 1
33%

1 < x = 2
56%

Legend:
- $0 < x <= 1$
- $1 < x <= 2$
- $2 < x$
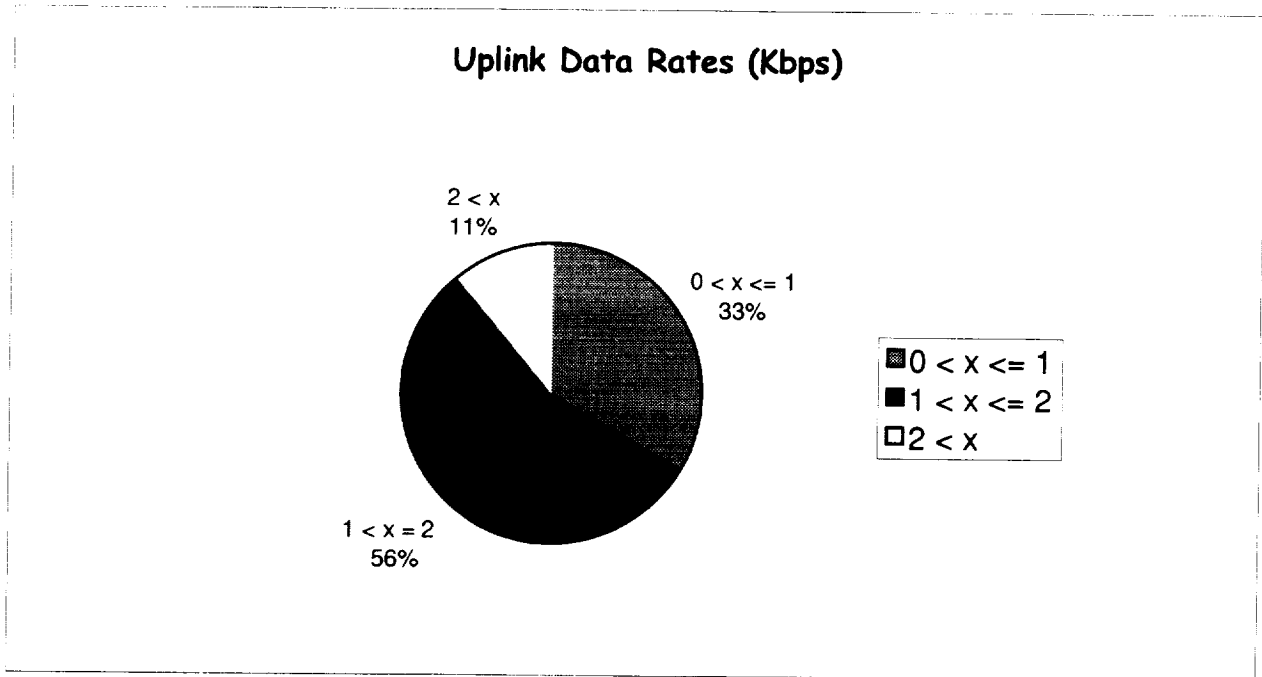
2.4.2 Downlink Data Rates

The downlink data rates that comprise the chart below were obtained from a table (see Appendix A) where for each spacecraft, a single downlink maximum data rate was identified and parsed. From the chart below, it can be seen that approximately 49% of the downlinks have data rates less than or equal to 1 Mbps and that approximately 78% of the downlinks have data rates less than or equal to 5 Mbps. The high data rate downlinks belong to missions associated with the Earth Observing System (EOS) Program, specifically LANDSAT-7, TERRA, and PM-1 with maximum downlink data rates of 150 Mbps.

Downlink Data Rates (Kbps)

50000 < x <= 150000
11%

0 < x <= 100
21%

5000 < x <= 50000
11%

100 < x <= 500
17%

1000 < x <= 5000
29%

500 < x <= 1000
11%

Legend:
- 0 < x <= 100
- 100 < x <= 500
- 500 < x <= 1000
- 1000 < x <= 5000
- 5000 < x <= 50000
- 50000 < x <= 150000
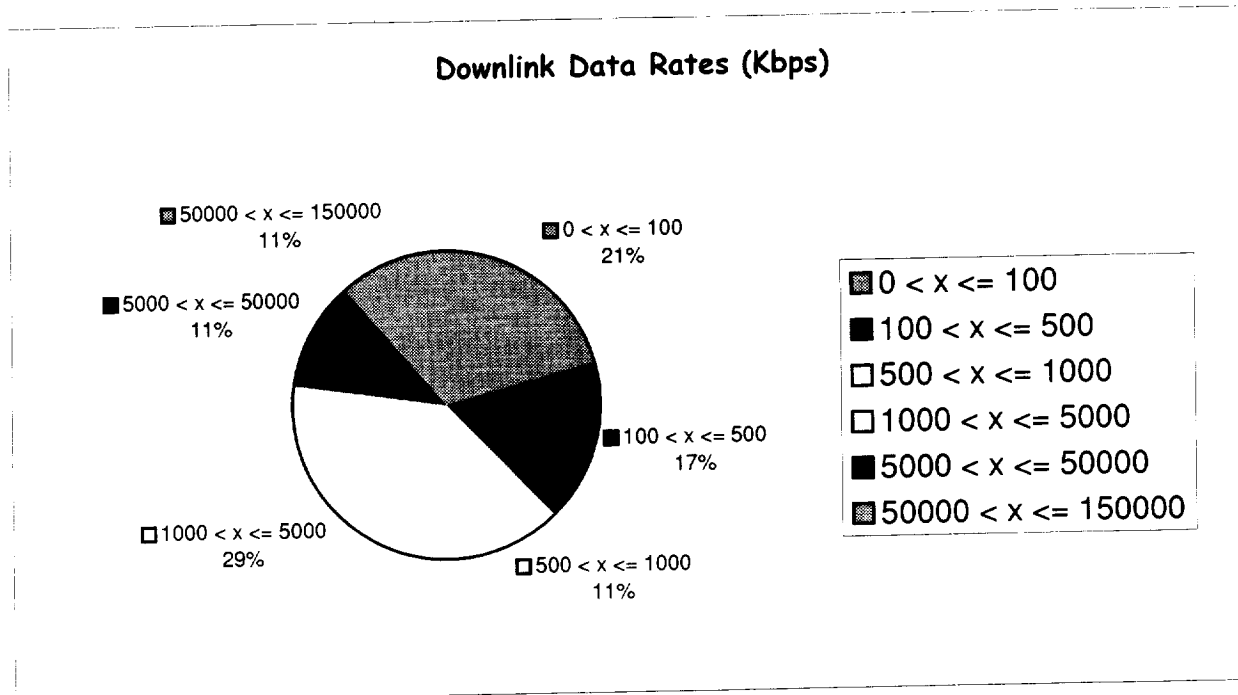
2.4.3 Uplink Frequencies

The uplink frequencies that comprise the chart below were obtained from a table (see Appendix A) where for each spacecraft, all possible uplink frequencies were identified and parsed. The uplink frequency spectrum is clearly dominated by S-Band, accounting for over 80% mission frequency use. A correlation between the extremely low uplink data rates and the dominance of S-Band uplinks can be drawn.

Uplink Frequency Band

VHF
2%

Ka Band
4%

S Band
80%

X Band
14%

- ▦ S Band
- ■ X Band
- ☐ Ka Band
- ☐ VHF
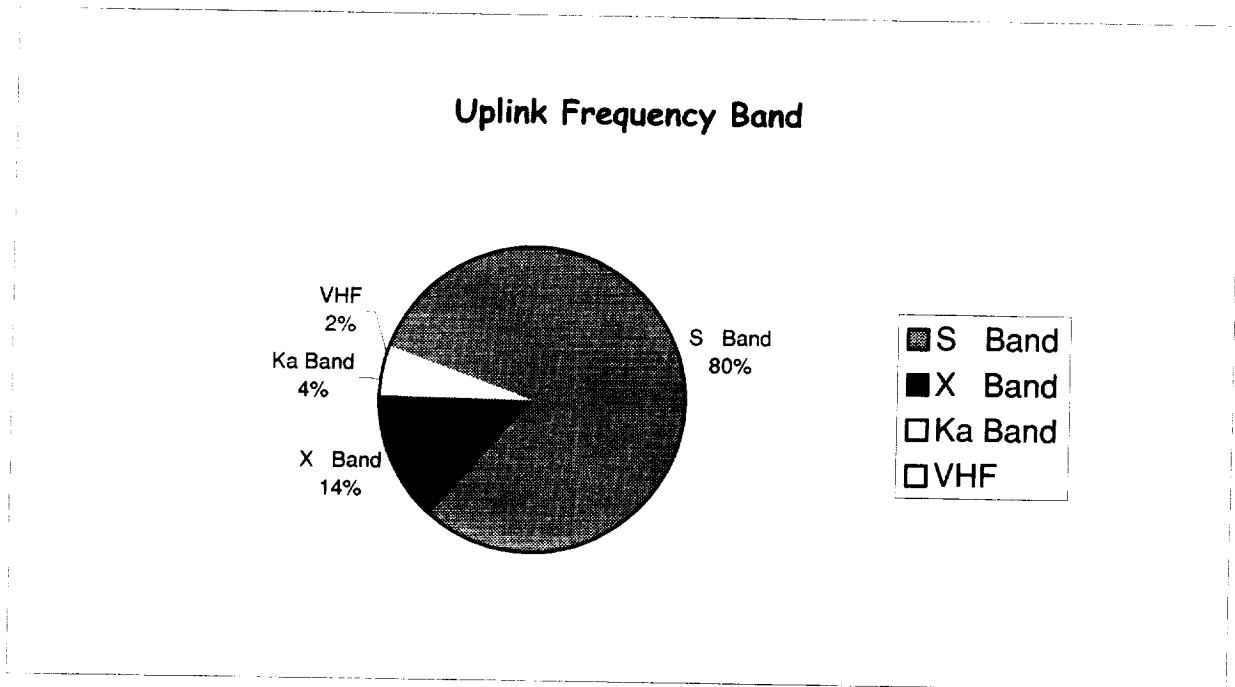
2.4.4 Downlink Frequencies

The downlink frequencies that comprise the chart below were obtained from a table (see Appendix A) where for each spacecraft, all possible downlink frequencies were identified and parsed. As can be seen, downlink frequency use is roughly evenly divided between S and X bands, with VHF, L, Ku, and Ka bands consuming the remainder. The reliance upon VHF is due to the IMP-8 Mission, launched in October 1973 with a projected lifetime of 27 years.

Downlink Frequency

S Band
49%

L
2%

VHF
2%

Ku Band
5%

Ka Band
5%

X Band
37%

Legend:
- S Band
- X Band
- Ka Band
- Ku Band
- VHF
- L
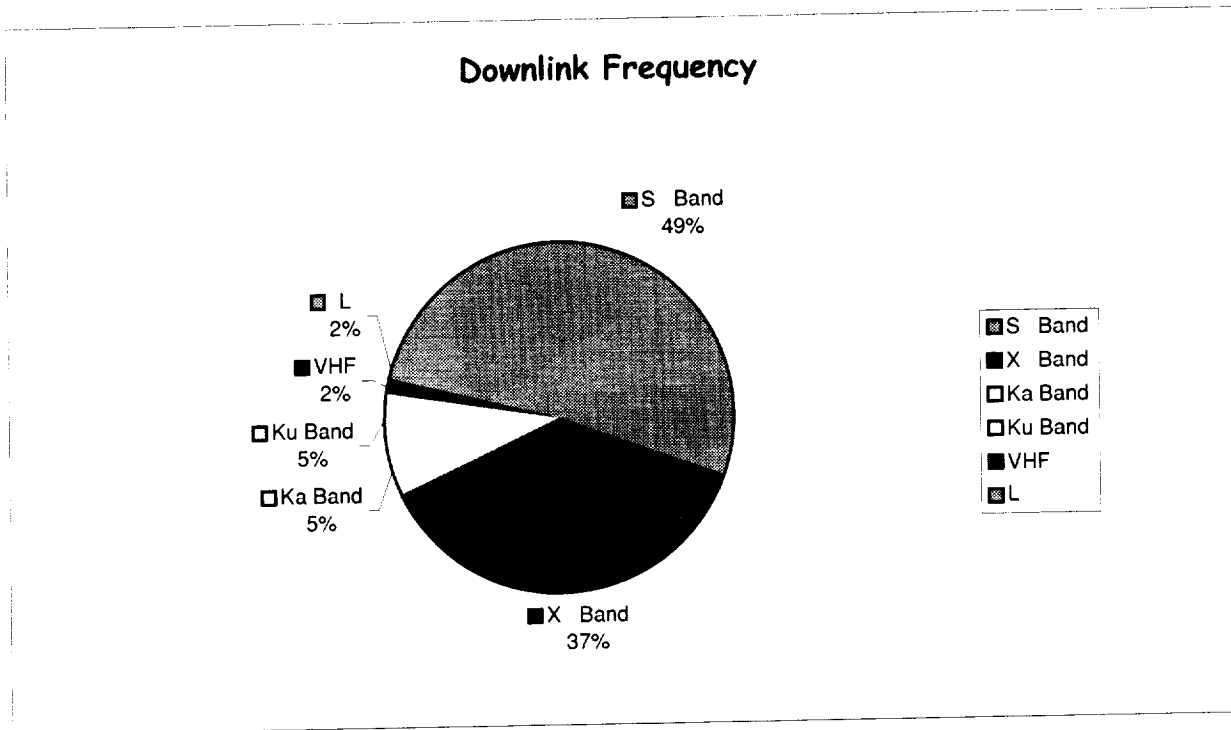
2.4.5 Apogee and Perigee Altitudes

The orbital parameters of apogee and perigee altitudes were included because of the various impacts that they have in designing a satellites communications support infrastructure (e.g., location and number of earth stations and link budgeting equations).

Apogee Altitudes (Km)

- 0 < x <= 500 — 8%
- 500 < x <= 700 — 26%
- 700 < x <= 900 — 22%
- 900 < x <= 1500 — 2%
- 1500 < x <= 36000 — 10%
- 36000 < x — 32%

Perigee Altitudes (Km)

- 0 < x <= 500 — 12%
- 500 < x <= 700 — 25%
- 700 < x <= 900 — 19%
- 900 < x <= 1500 — 4%
- 1500 < x <= 36000 — 10%
- 36000 < x — 30%
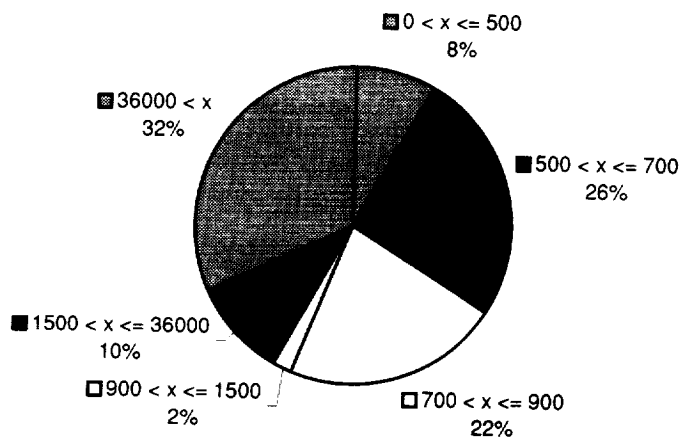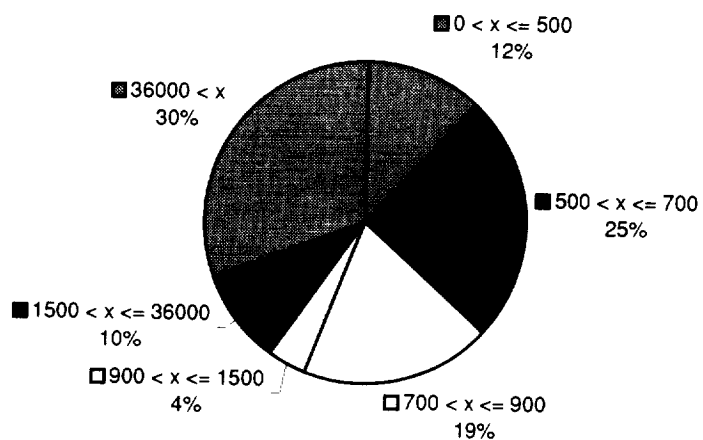
2.4.6 Orbital Inclination

An orbital factor influencing the design of spacecraft terrestrial communications support is orbital inclination. For highly inclined orbits, higher earth station elevation angles at the higher northern and southern latitudes must be planned. Additionally, for highly inclined orbits, earth station designs must account for tracking the satellite and the necessity for switching from a setting to a rising satellite. Variation of distance and satellite Doppler effects must be considered.

From the chart below, it can be seen that approximately 60% of the base set of mission satellites have inclinations greater than 60% and that 37% have retrograde orbits. It should be noted that a significant amount of the missions exhibiting retrograde orbits (> 90 degrees) belong to the EOS program and have downlink data rates of 150 Mbps.

Orbit Inclination (Deg)

- 0 < x <= 30 — 22%
- 30 < x <= 60 — 19%
- 60 < x <= 90 — 22%
- 90 < x — 37%
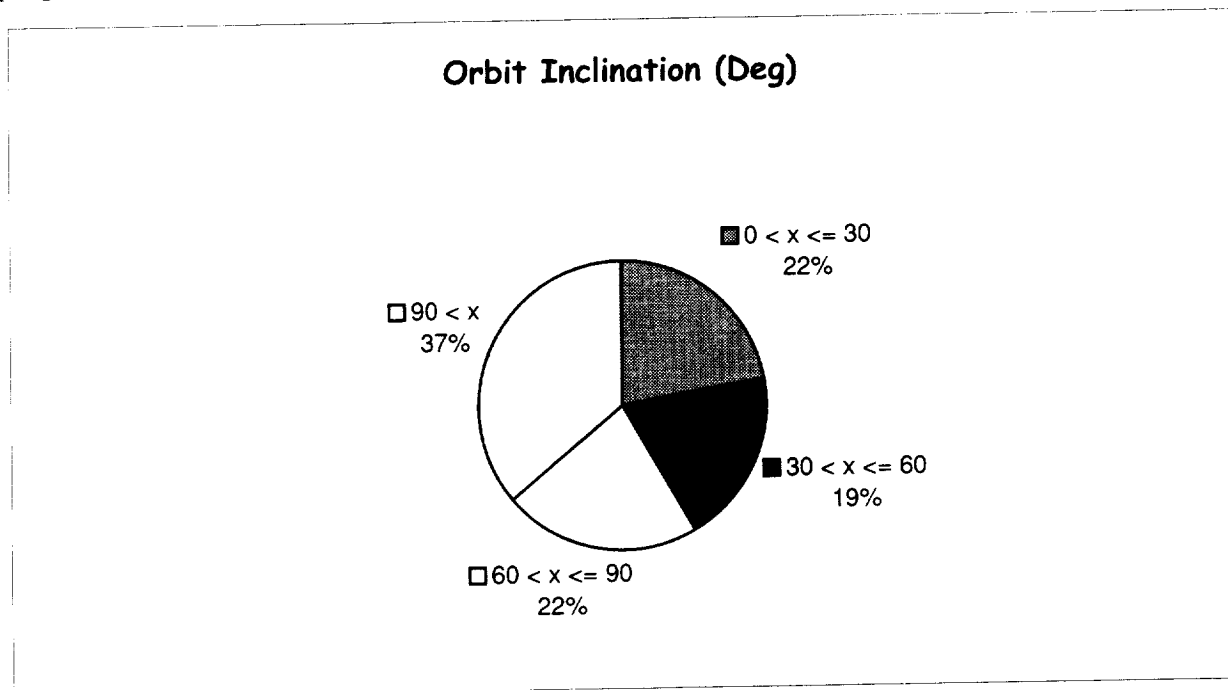
2.4.7 TDRSS Use

Roughly one-fourth of the satellites in the base set will use TDRSS for a variety of services including ranging, clock correlation, housekeeping, and mission telemetry and commanding. It might be surmised that a disproportionate use of total bandwidth is used by TDRSS customers. However, this does not appear to be the case. It was determined that approximately 23% of the downlink bandwidth is used by TDRSS customers. This is because of all the missions in the base set, only one (TERRA) will be using TDRSS as its primary link to downlink its mission data, both in playback and realtime modes. TERRA will use TDRSS S-Band Single Access (SSA) for realtime and K-Band Single Access (KSA) for playbacks.

TDRSS Use

Unknown
8%

Yes
26%

No
66%

- Yes
- No
- Unknown
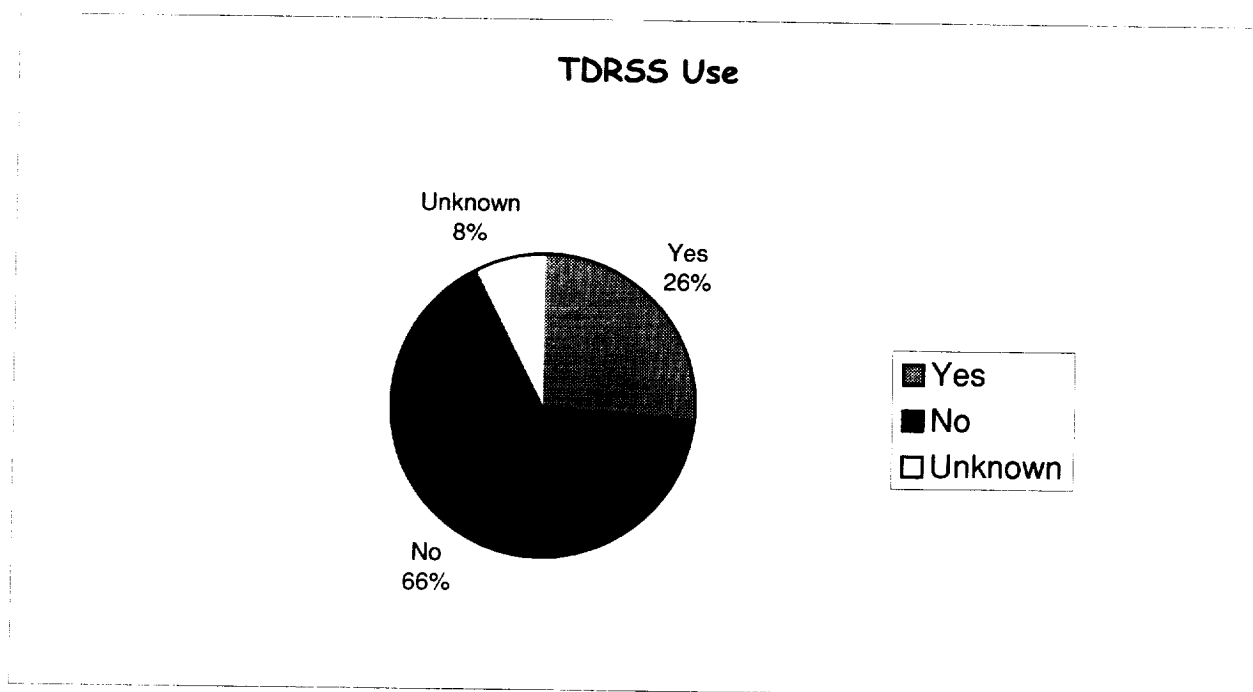
Information sources for this section:

- NASA Web Pages (too numerous to list)

- Telephone calls and emails (too numerous to list)

- *Mission Requirements and Data Systems Support Forecast*, Updated 4 June 1999, Network and Mission Services Office, Code 450

- *NASA Strategic Plan* (with 1999 Interim Adjustments)

3. COMMERCIAL SERVICES, PRODUCTS, AND TRENDS

3.1 Commercial Satellite Services

There is a large variety of commercial satellite communication services available now or planned for the near future. These services are available with satellites located at various orbits (i.e., GEO, LEO, and MEO), operated at various frequencies (i.e., VHF, UHF, L-Band, C-Band, Ku-Band, and Ka-Band), and providing various ITU services. The ITU services are Broadcast Satellite Service (BSS), Fixed Satellite Service (FSS), and Mobile Satellite Service (MSS). In terms of the complexity required to acquire and use the commercial satellite communication services, the services can be classified into two categories: "off-the-shelf" services and "leased transponder" services [VUON].

This section provides definitions of these two service classes and key features of candidates from these two classes.

3.1.1 Off-the-Shelf Services

Off-the-shelf services, like terrestrial cellular/PCS phone services, are simple to acquire and use [VUON]. A user buys or rents off-the-shelf terminals, registers with the service provider to set up an account, installs equipment at the premises, and then uses the services. There are no design efforts and no license filings required. The whole process typically takes only minutes or hours.

Relevant off-the-shelf services are further categorized into "little LEO," "big LEO," "big MEO," "L-Band GEO," "multimedia LEO," and "multimedia GEO." Note that there are other commercial off-the-shelf satellite communication services not relevant to NASA's relay communication requirements such as direct broadcast satellite (DBS) services that provide direct satellite broadcast TV programs to home [CHRI] and satellite digital audio radio services (SDARS) that provide direct satellite broadcast digital audio radio programs [CAMP]. Characteristics of representatives of these relevant off-the-shelf services are provided in Table 3.1.

Little LEO Services

Little LEO services are also called "non-voice, non-GEO" services, as they do not support voice communication and use satellites in LEOs [KIES]. The systems use small and simply designed satellites and operate at MSS VHF (Orbcomm operates from 137 to 150 MHz for service and feeder links [PARK]). There were at least eight FCC filings for the services [KIES], but most of them have been withdrawn or have not yet been built. Orbcomm, which is currently in operation with a constellation of 34 active satellites, is the representative of the little LEO services in Table 3.1 [PARK].

Big LEO Services

Big LEO services are also called "satellite cellular phone" services that provide interactive digital voice and low bit rate data to hand-held terminals worldwide. They operate at MSS S or L-band (users' frequencies). They have gateways for connection to the public switched telephone network (PSTN). Iridium [KOLS] was deployed but filed for Chapter 11 protection on August 13, 1999, and ceased operations in March 2000 [SCHW]. Globalstar [DIET] was scheduled to be in

full operation in 1999. Other big LEO systems have probably been withdrawn or have not yet been built.

Iridium was a constellation of 66 LEO satellites whose nominal altitude was 780 km. It was the first commercial system that used inter-satellite links (ISLs) operated at ISL Ka-band, 22.55–23.55 GHz, to route its traffic. It allowed direct terminal-terminal connection (i.e., connection without going through a gateway station). Its user links used multiple-carrier time division multiple access (MC-TDMA) and operated at MSS L-band (1616.0–1626.5 MHz) with 48 spot beams/satellite. The feeder links that connect the satellites with gateway stations operated at FSS Ka-band (uplink 27.5–30.0 GHz and downlink 18.8–20.2 GHz). Iridium supported a user data rate of 2.4 kbps.

Globalstar is a constellation of 48 satellites whose nominal altitude is 1,400 km. Unlike Iridium, it does not have ISLs. It uses code division multiple access (CDMA). Its user link frequencies are L and S-band and feeder link frequencies are C-band (7/5 GHz).

Big MEO Services

Big MEO services are the same as Big LEO services except that the satellites are at MEOs (altitudes of 8,000–20,000 km) instead of LEOs (altitudes of up to 2,000 km) [MAKI]. There were two filings for Big MEO services: ICO and Odyssey. Since then, a patent right infringement dispute associated with the use of MEOs has been resolved, and TRW, owner of Odessey, has scrapped its Odessey project and become a prime contractor for building the ICO system. ICO [MAKI] is a constellation of 10 satellites in two MEO orbits (nominal altitude of 10390 km). Its user links use multiple-carrier time division multiple access (MC-TDMA) and are operated at MSS L-band (1616.0–1626.5 MHz) with 163 spot beams/satellite. The feeder link frequencies are C-band (7/5 GHz). The user data rate supportable is 2.4 kbps. Note that ICO filed for Chapter 11 protection on August 27, 1999.

L-Band GEO Services

L-Band GEO services are off-the-shelf services that use GEO satellites and operate at MSS L-band (users' link frequencies): Aces [TAYL], AMSC/TMI [TMI], and Inmarsat. Inmarsat services are the only services that provide global coverage (except for the pole areas).

Inmarsat [VUON], [SCHU] is an international organization with more than 80 signatory country members. COMSAT is the U.S. signatory. It was founded to provide communication services to ships. But in the late 1980s, Inmarsat extended its services to land and aviation users. Inmarsat divides the world into 4 regions: AOR-W (Atlantic Ocean Region-West), AOR-E (Atlantic Ocean Region-East), IOR (Indian Ocean Region), and POR (Pacific Ocean Region). Each Inmarsat region is served by an Inmarsat satellite that connects an Inmarsat user terminal, operated at 1.6/1.5 GHz (L-band) to one of the region's gateway stations, operated at 7/3 GHz (C-band). Each satellite has wide (global) C-band and L-band coverage. Inmarsat-3 (third generation) satellites additionally have coverage with fixed spot beams [SCHU]. Inmarsat gateway stations are used to record call duration for billing purposes and to connect calls to/from the public switched networks (PSTN, ISDN, PLMN) and the users' private networks on a prearranged basis. A call between two Inmarsat terminals requires double satellite hops via a gateway station.

Through the four regional satellites, Inmarsat offers the following off-the-shelf services: Inmarsat-A, Inmarsat-B, Inmarsat-C, Inmarsat-C, Inmarsat-D/D+, Inmarsat-M, Inmarsat-Mini-M, and Inmarsat-Aero (Aero-C, H, I, and L) [VUON], [COM1]. Each service requires its own specific off-the-shelf terminals. Services that may be suitable for NASA's relay communication requirements are Inmarsat-A, Inmarsat-B, and Inmarsat-Aero. Inmarsat-A or Inmarsat-B provide the highest user bit rates (64 kbps), while Inmarsat-Aero accommodates the fastest movement (the highest Doppler effects and fastest tracking) of its terminals.

Multimedia LEO Services

Multimedia LEO services are off-the-shelf services that use LEO satellites and provide multimedia (broadband) communication services. There were two systems that filed with the FCC for the multimedia LEO services: Teledesic and Celestri. Motorola, however, scrapped its Celestri system upon agreement with Teledesic management to become a major owner and the prime contractor for the design of the Teledesic system. That agreement has since been abandoned, and Motorola is not planning any new system.

Teledesic is planned as a global, broadband "Internet in-the-Sky" with a constellation of 288 LEO satellites (nominal altitude of 10,390 km) to be operated at FSS (NGSO) Ka-band (uplink: 28.6–29.1 GHz, downlink: 18.8–19.3 GHz) [TELE]. From the original filing, the number of satellites was 840 at an altitude of 700 km [MCCA]. It was then officially modified to 288. When Motorola was involved with the Teledesic program as a partner and a prime contractor, there were rumors that the number of satellites were further reduced to less than half to reduce cost and to compromise with Motorola's Celestri Constellation.

Teledesic utilizes spot beams to reduce prime power requirements from the satellites and antenna sizes from user terminals. With spot beams, the allocated Ka-band can also be reused. Teledesic uses multiple-carrier time division multiple access (MC-TDMA) with TDMA bursts (whose bandwidths may vary) being assigned to users on a demand basis. Its user terminals have sizes ranging from 0.2 to 1.8 m to support user data rates from 2 to 64 Mbps [TELE].

Because Teledesic uses IP as a network access protocol, it directly supports connection oriented (TCP) and connectionless (UDP) services and any IP-based application services.

Multimedia GEO Services

Multimedia GEO services are off-the-shelf services that use LEO satellites and provide multimedia (broadband) communication services. Hughes' Spaceway [SPAC] and Lockheed Martin's Astrolink [ASTR] are the front runners.

Operating at the FSS, geostationary orbit, Ka-band (uplink: 29.5–30.0 GHz, downlink: 19.7–20.2 GHz), Spaceway will consist of interconnected regional GEO satellite systems. The first regional system (North America) is scheduled to provide services in 2002 with operating GEO satellites to be located at 99°W and 101°W. Spaceway has also been granted orbital slots at 25°E, 49°E, 54°E, 101°E, 111°E, and 164°E. Like Teledesic, Spaceway is "an IP-router in the sky" that utilizes onboard digital processor, packet switching, and spot beam technology. It also utilizes MC-TDMA on its uplink where TDMA bursts are assigned to its users on a demand basis. Its user terminals have sizes ranging from 0.7 to 2.4 m to support user data rates from 16 kbps to 6 Mbps [SPAC].

3.1.2 Leased Transponder Services

Off-the-shelf services may not meet users' requirements in terms of connectivity, availability, security, bit-rate, etc. An alternative is to design one's own satellite communication network using space segment resources (e.g., transponder bandwidth and RF power) that can be leased from a commercial satellite operator (e.g., Intelsat). Both U.S. and foreign license filings will also likely be required. The whole process can take months or years.

Due to design and cost, only FSS GEO satellite operators offer leased transponder services. MSS satellites (e.g., Inmarsat and Iridium) typically operate at L-band or S-band, and their allocated bandwidths are too limited to be used for leased transponder services. LEO/MEO systems, due to their coordinated operation among their satellites and gateways, are not suitable for leased transponder services.

FSS GEO transponders available for lease are plentiful. They are available at C-band and Ku-band now and Ka-band in the near future. Nevertheless, Intelsat's global C-band transponders are the only ones that can be used to meet typical full coverage requirements of NASA's LEO missions. Commercial Ku (and later Ka) band satellites employ spot or regional beam antennas in order to optimize link gain in population areas where likely customers reside. Intelsat's global C-band transponders have nominal global coverage (line-of-sight coverage) and a usable bandwidth of 36 MHz. To meet the full coverage requirements, it is necessary to lease these global C-band transponders from three Intelsat satellites located in the different region: Pacific Ocean Region (POR), Atlantic Ocean Region (AOR), and Indian Ocean Region (IOR). It is also necessary to have at least three earth stations for access to the LEO spacecraft via these three satellites. The amount of space segment required to be leased (e.g., one-quarter, one full, or two full transponders) depends on the data rate requirements for the LEO missions and the design of the links (modulation and FEC coding used).

3.2 Areas of NASA-Commercial Convergence and Divergence

Section 3.1 examined commercial satcom services. In this section, we synopsize the results of a brief survey of other commercial offerings and developments including support systems, products, components, and software. The purpose is to identify areas of convergence and divergence between commercial trends and IOA goals.

3.2.1 NASA-Commercial Convergence

TCP/IP Via Satellite

IP networks are proliferating worldwide, driven by the need of countries to become competitive in a globalized economy. Satellite relay has become a profitable method for connecting Internet service providers (ISPs) in foreign countries to the U.S. Internet backbone. Satellite service operators are stating revenue growth of 100% per year or better in this market [IVSC]. The operators have found solutions for carrying TCP/IP networks over GEO satellite transponder channels and are now routinely using these protocols. Some providers are using TCP/IP with no adjustments or modifications. However, there are a number of problems that can result from using

Table 3.1 Features of Commercial Services

System (# Sats)	User Link Freq.	User Data Rate	Modulation Access	Network Protocol	User Terminal
Little LEO: Orbcomm (34), now Alt.: 825 km	VHF (MSS) 137–150 MHz	forward: 2.4 kbps return: 4.8 kbps	dedicated	– dedicated – gateway connected to PSTN and X.400 and X.25 networks	hand-held, dedicated
Big LEO: Iridium (66), now Alt.: 780 km	L-Band (MSS) 1616.0–1626.5 MHz (for U/L & D/L)	forward: 2.4 kbps return: 2.4 kbps	dedicated QPSK/TDMA	– dedicated – gateway connected to PSTN	hand-held, dedicated
Big MEO: ICO (10), 2000 Alt.: 10,390 km	S-Band (MSS) U/L: 2170–2200 MHz D/L: 1980–2010 MHz	forward: 2.4 kbps return: 2.4 kbps	dedicated QPSK/TDMA	– dedicated – GSM-based – gateway connected to PSTN, ISDN	hand-held, dedicated
L-Band GEO: Inmarsat (4), now	L-Band (MSS) U/L:1626.5–1646.5 MHz D/L:1530.0–1545.0 MHz	forward: ≤ 64 kbps return: ≤ 64 kbps	dedicated	– dedicated – gateway connected to PSTN, ISDN	size varied with services, dedicated
Multimedia LEO: Teledesic (288), 2003 Alt.: 1375 km	Ka-Band (FSS) U/L: 28.6–29.1 GHz D/L: 18.8–19.3 GHz	forward: 2–64 Mbps return: 64 Mbps	dedicated QPSK/TDMA	– IP-based 0.2	~1.8 m, dedicated
Multimedia GEO: Spaceway (12), 2002	Ka-Band (FSS) U/L: 29.5–30.0 GHz D/L: 19.7–20.2 GHz	forward: 16 kbps–6 Mbps return: 16 kbps–6 Mbps	dedicated QPSK/TDMA	– IP-based 0.7	~2.4 m, dedicated

TCP and IP in a GEO satellite channel due to the long propagation delay and the error characteristics. A long delay can limit the throughput of a TCP connection, while a high error rate is interpreted as congestion, bringing into play congestion avoidance algorithms. Extensive research has been and is being performed on these problems by academia, NASA, and private enterprise, including a number of experiments over NASA's ACTS satellite.

Products exist for extending TCP/IP networks over GEO satellite relays. Examples include Mentat's SkyX Gateway [MENT] and Comsat's Link Accelerator product line [COM2].

The use of TCP/IP from a LEO platform to ground involves a different set of problems than encountered in the typical commercial GEO/FSS scenario described above. For example, the propagation delay is short in the LEO environment. Another major difference is that the LEO orbiters are mobile, so their location in the network is constantly changing. This means that the routing of IP packets must change as well, requiring the network's routers to keep track of the changes. The problem of mobile LEO IP nodes is related to the problem of mobile IP in terrestrial wireless networks, although there are significant differences. One difference is that the location of LEO satellites is predictable. Commercial solutions for terrestrial wireless networks may be applicable to the IOA.

At least one company, Sterling Satellite Communications Co., is developing an IP solution specifically for its LEO space-based communications network. It includes onboard fast packet switching in a digital signal processor (DSP) chip [SSCC].

Fiber Network Trends

Fiber networks are the chief competition for the satellite communications industry. Fiber trends will have an impact on the degree of success of new commercial satellite ventures such as Teledesic. New fiber technology such as dense wavelength division multiplexing changes the economics of fiber. Also, new fiber projects specifically aimed at the IP market such as Global Crossing [GLOB] and Project Oxygen [PROJ] will push down prices for international fiber bandwidth. These developments were not foreseen at the time the market analysis was done for Teledesic and will likely be a significant factor in whether or not such a system is deployed.

Direct to Customer

In the commercial world there is a trend toward "direct to customer," or downlinking from the satellite directly to the customer premises. This coincides with the IOA plan for using direct data distribution to automatically track VSATs. Commercial VSATs resemble the low-cost miniature autonomous ground stations (MAGS) described in the IOA Baseline [CSOC], except that they usually have fixed, not steerable antennas. The latest generation of Ku band VSATs is available for general broadband data service up to 45 to 58 Mbps, with a narrowband return channel. For example, see the Web-Sat product, which operates over Eutelsat [WEBS]. A commercial autonomous tracking ground station is discussed under Ground Support Systems below.

Ku Band VSAT Mass Market

The mass market in VSATs is a development that could be exploited by NASA by using direct data distribution with the miniature autonomous ground stations described in the IOA. The VSAT mass market, including DBS, has led to the development of mass-produced Ku band components. The components of this mass-produced technology could be used to build autono-

mous tracking ground stations of the kind envisioned in the IOA. If NASA moves to Ka band as the IOA mandates, these components would not be applicable. (It may be noted that NASA has already developed a Ka-band MMIC front end for commercial applications [NTB].)

Steerable parabolic antennas would be needed for the earth station, or, for greater mechanical reliability and a lower profile with lower wind resistance, steered-beam phased array antennas could be used.

Ground Support Systems

Commercial imagery systems are being deployed in greater numbers. They closely resemble their NASA counterparts and have very similar ground support requirements. These ground support systems could be used by NASA.

There is a strong resemblance between the two domains in how the support infrastructure is designed and operated. The owners of these systems each operate them as independent systems, with proprietary purpose-built operations centers and ground stations. However, there are customers such as the U.S. military who would like to downlink imagery from multiple commercial and government civilian satellites. The military is particularly interested in using the new 1-meter resolution systems such as Space Imaging's Ikonos and Orbital Sciences' Orbview series. Also of military interest are satellites like the Canadian 3-meter resolution synthetic aperture radar (SAR) satellite Radarsat-2.

This has led to the development of commercial products such as Fast Tracs, offered by MacDonald Dettwiler, that essentially accomplish the goal of an integrated architecture for the space-ground interface. This product was developed for the military and is a transportable ground station capable of interfacing to any of the commercial imaging satellites and processing their imagery, including the SAR satellites [MACD].

There are firms offering ground support systems today. Allied Signal Technical Services, a major subcontractor in the CSOC project, has announced a command, control, and communications system called DataLynx that will be offered as a commercial service. It appears to be aimed at the IOA application, among others. It uses an autonomous tracking ground station called LEO-T that was developed for commercial and government LEO satellite ground support. It has a 13-meter antenna and operates at L, S, and X band. An installation at Fairbanks, Alaska, supports a number of NOAA and Air Force weather satellites [ASTS].

Ka-band ground stations are also being developed commercially. Deskin Research Group, the contractor that is building the Leo One USA satellite constellation, claims to have developed a portable Ka-band ground station for the Teledesic system [DESK]. Another company that makes very small tracking ground stations is Aero Astro [AERO].

Automated Operations

Automated mission operations is an area where commercial products are becoming available. Recently, the Landsat 7 project office chose a commercial off-the-shelf software product to automate its mission control operations. The product is called Altairis MCS, by Altair Corporation [ALTA].

There is a potential for using the network and operations management software developed for systems such as Iridium insofar as it has common functionality with the IOA. (NASA's fleet of near-earth missions could be regarded as a LEO constellation.)

Commercial providers of network management software such as Telcordia are developing self-managing network software to reduce manpower requirements at network operations centers.

Commercial Satellite System Components

The commercial LEO systems such as Globalstar, Teledesic, and others will lead to a quasi mass market in satellite components, including the spacecraft platform, steered beam phased array antennas, ISLs, space qualified processors, and Ka band space-qualified components. For example, General Dynamics Information Systems is developing a 450 MIPS radiation hardened PowerPC processor for the Final Analysis Communications LEO system [MAE].

Commercial LEO systems are also resulting in solutions for IP networking in space. Sterling Satellite Communications, already mentioned, is developing such a solution. It consists of a space-qualified DSP chip and software.

In a related development, Intel announced in December 1998 that it would provide a royalty-free license to Sandia for its Pentium processor design to allow Sandia to develop radiation-hardened versions for space applications.

Storage Technology

Of particular interest for space-ground communications architectures is the projected improvement in memory and storage technology for onboard storage. A ten-year time horizon may encompass three generations or a 64-fold increase in solid state memory density, assuming no breakthroughs. A present generation solid state recorder is Landsat 7's 380 gigabit recorder [LAND]. A projection three generations into the future would result in a 24 terabit recorder. Nanochip, Inc., claims it will soon offer a non-volatile, solid-state storage device capable of 1.4 terabytes of storage in a 3-inch disk drive form factor [NANO]. This is equivalent to a full day's data collection for Landsat 7.

Security

Commercial security protocols and techniques, especially encryption, are reaching a level of robustness that may make them acceptable for NASA's most secure applications such as spacecraft command and control.

Teleports

Commercial teleports are good locations for NASA ground stations because of the terrestrial network access point and the availability of local maintenance personnel.

3.2.2 NASA-Commercial Divergence

Divergences between commercial applications and NASA mission needs were surveyed in order to suggest how the respective systems requirements and communications architectures may differ.

Economies of Scale

One of the chief reasons for using commercial products is the lower cost derived from an economy of scale. But because of the need for space qualification, the use of commercial-quality parts in spacecraft is limited. The cost-effectiveness of using commercial parts or subsystems as opposed to using custom-designed parts must be carefully evaluated.

User Terminals on the Ground Versus in Space

The user terminals in the commercial world are mostly on the ground, while a small number are in aircraft. In the context of the IOA, however, the "user" terminals relevant to this study are spacecraft. Commercial satcom services are not designed to interface to spacecraft.

Population Coverage Versus Geographic Coverage

Commercial networks aim to maximize population coverage, whereas the IOA intranet needs to achieve maximum geographic coverage. For example, commercial communications satellites tend to have footprints and transponders allocated to areas of significant population.

Higher Frequencies Up to Optical

Commercial applications tend to require real time transfer of data to the customer premises, whereas many NASA science missions can tolerate delays in data delivery and can downlink to remote locations. This has implications for advanced technologies such as an optical space-to-ground downlink. Optical downlinks will require geographic diversity to avoid cloud cover. This is feasible for NASA missions but is probably not commercially viable for consumer and enterprise networking.

TCP/IP

Most of the work on TCP/IP via satellite in the commercial world concerns the GEO FSS. For the IOA, the IP nodes will mostly be in LEO, with different problems as discussed in the previous section.

Ku Band and Ka Band

Most of the commercial world is using Ku band as its highest frequency and will do so for a considerable time to come. The commercial transition to Ka band will likely be slower than within NASA. There are currently very few commercial satellites carrying Ka-band transponders.

Small Versus Large Spacecraft

The trend in commercial spacecraft, at least in the FSS and BSS, is toward larger systems, while at NASA the trend is toward smaller spacecraft. The reason that FSS/BSS satellites are being designed at higher power levels is to drive down the cost of the user terminal. The cost of the satellite is amortized over thousands or millions of fee-paying customers. NASA, on the other hand, is trying to drive down the cost of spacecraft, in part to pave the way for low-cost access to space. In the design of small spacecraft, there is an incentive to reduce the complexity of the spacecraft, for example, less onboard processing rather than more. This runs counter to the trend in commercial satcom.

4. COMMERCIAL INTEROPERABILITY ISSUES

This section presents a high level assessment of issues that will arise if NASA mission platforms are to interoperate with commercial satellite systems. These issues fall into two main areas: the feasibility of interfacing to commercial satellites for data relay and the feasibility of using IP.

4.1 Data Relay Service Interoperability

NASA's LEO missions were compiled and described in Section 2. These missions, depending on their purposes, require NASA to provide either relay or direct-to/from-ground (i.e., non-relay) communication services to meet their command, telemetry, and scientific data download requirements.

For the direct-to/from-ground communication services, NASA is using its S, X, or Ku-band LEO remote ground stations. According to the IOA [CSOC], NASA is considering decommissioning these LEO remote ground stations and replacing them with low-cost, standardized, miniature autonomous (Ka-band) ground stations (MAGS). Assessment of use of commercial technology for the design of MAGS will be addressed in Section 5, the technology assessment section.

For the relay communication services, NASA is using its GEO tracking and data relay satellites (TDRSs) for communication with user LEO spacecraft at S, Ku-band, and Ka-band. Ka-band will be available with the future TDRS-H, I, J satellites.

NASA has also participated with European Space Agency (ESA) and Japanese National Space Development Agency (NASDA) in the Satellite Network Interoperability Panel (SNIP). Through SNIP, a set of (S-band and Ka-band) interoperability parameters was established to also allow NASA to provide the relay communication services via ESA's relay satellite system, including the current Artemis satellite [SBAR] and future data relay satellites (DRSs) [GIUB] and NASDA's relay satellite system (with future DRTS satellites [HOTT]).

According to the IOA, NASA is also considering use of commercial satellite communication services to complement or replace its relay communication services to reduce cost. There are issues, however, on the use of commercial satellite communication services, e.g., feasibility and interoperability. These issues are discussed in this section.

4.2 NASA Data Relay Capabilities

NASA provides its relay communication services through its TDRSS [TDR1]. Table 4.1 provides key features of NASA's relay communication services to NASA's user LEO spacecraft. The key features listed for each relay satellite are operating frequency band (for space-space links), maximum supportable user data rate, modulation/access, and network protocol.

The space segment of the TDRSS consists of the 6 on-orbit TDRSs (F1, F3, F4, F5, F6 and F7; F2 failed during launch with STS Challenger 2) and TDRS-H, I, J to be launched in the near future. Three of the current TDRSs are available for operational support at any given time and are located at 41, 174, and 275 degrees west longitude to provide full (100%) coverage to LEO spacecraft. The other TDRSs provide ready backup in the event of failure to an operational spacecraft and, in some specialized cases, resources for target of opportunity activities [TDR1]. As stated earlier in the introduction section on the SNIP, the space segment, in a broad sense, also comprises ESA and NASDA's relay satellites (i.e., ARTEMIS, DRSs, and DRTSs).

Table 4.1 Features of NASA's Relay Communication Services

Relay Satellite	User Link Frequency	Max. User Data Rate	Modulation/Access	Network Protocol

NASA:
TDRS (F1 - F7) (current)
TDRS-H, I, J (future)
	– S-Band (SRS/SOS)
	  fwd: 2020.4–2123.3 MHz
	  rtn: 2200.0–2300.0 MHz
	  (all satellites)
	– Ku-Band (SRS)
	  fwd: 13.4–14.2 GHz
	  rtn: 14.5–15.3 GHz
	  (all satellites)
	– Ka-Band (ISS)
	  fwd: 22.55–23.55 GHz
	  rtn: 25.25–27.50 GHz
	  (TDRS-H, I, J)
		Single Access (SA):
		– forward (S): 0.3 kbps
		– return (S): 6 Mbps
		– forward (Ku): 25 Mbps
		– return (Ku): 300 Mbps
		– forward (Ku): 50 Mbps
		– return (Ku): 600 Mbps
		Multiple Access (MA):
		– forward (S): 10 kbps
		– return (S): 150 kbps, 3 Mbps
		  (TDRS-H, I, J)
			– dedicated
			– QPSK or BPSK
			– FEC rate 1/2 or 1/3
			– fixed schedule access (current)
			– demand assigned access (future)
			– CDMA (return MA)
				– dedicated (current)
				– IP-based (future)

ESA:
ARTEMIS (current)
DRS (future)
	– S-Band (SRS/SOS)
	  (all satellites)
	– Ka-Band (ISS)
	  (all satellites)
		compatible with NASA via SNIP	compatible with NASA via SNIP	compatible with NASA via SNIP?

NASDA:
DRTS (future)
	– S-Band (SRS/SOS)
	  (all satellites)
	– Ka-Band (ISS)
	  (all satellites)
		compatible with NASA via SNIP	compatible with NASA via SNIP	compatible with NASA via SNIP?

SRS: Space Research Services, SOS: Space Operation Services, ISS: Inter-Satellite Services

The TDRSS ground segment consists of two functionally identical ground terminals: Cacique, located near Las Cruces, New Mexico, and Danzante, the Guam Remote Ground Terminal [GRGT]. The Cacique and Danzante ground terminals, known collectively as the White Sands Complex (WSC), are used to communicate with TDRSs located in the Pacific and Atlantic Regions. The GRGT is used to communicate with the Indian Ocean Region TDRS (i.e., TDRS F3 located at 275 degrees west longitude) to eliminate the Zone of Exclusion (ZOE). As stated earlier in the introduction section on the SNIP, the ground segment, in a broad sense, also comprises ESA and NASDA's gateway stations that connect to ESA and NASDA's relay satellites.

User forward data (i.e., spacecraft command) are uplinked from the ground segment to the TDRSs and then to the user LEO spacecraft. User return data (i.e., spacecraft telemetry and scientific data) are downlinked from the spacecraft to the ground segment via the TDRSs. These forward and return data are currently transmitted on a fixed schedule basis. According to the IOA, this fixed schedule access will be replaced by an automatic demand access scheme to reduce cost, to make better use of the space segment resources, and to better serve the user spacecraft relay communication needs [ZIL1], [ZIL2]. The maximum supportable forward and return data rates (shown in the third column of Table 4.1) depend on many factors including: i) user link frequency used (S, Ku, or Ka-band); ii) single access (SA) or multiple access (MA) selected; iii) modulation (QPSK or BPSK) and FEC coding rate (1/2 or 1/3) used; and, iv) data types — Data Group 1 (i.e., PN spread) or Data Group 2 (i.e., non-spread), coherent or non-coherent [TDR2].

4.3 Commercial Service Interoperability General Assessment

4.3.1 ITU Service Compliance

To optimize usage of the Natural Frequency Spectrum, the International Telecommunication Union (ITU) of the United Nations, in its Radio Regulation publication [ITU], has classified radio emissions into ITU services. The Radio Regulation assigns frequencies to these services and has set constraints and rules to allow these services to operate without causing harmful interference to each other. The relay communication services provided by NASA are categorized by the ITU as Space Research Services (SRS), Space Operation Services (SOS), and Inter-Satellite Services (ISS) as shown in Table 4.1. On the other hand, commercial satellite communication services available now or in the foreseeable future are FSS, BSS, and Radio-Determination Satellite Services (RDSS). As discussed in Section 3.1, all candidate commercial satellite services are either MSS or FSS.

Thus, technically, by using commercial satellite services to meet relay communication requirements by LEO spacecraft, NASA will be in non-compliance with the ITU. Nevertheless, such non-compliance usage may be acceptable if NASA could show that the usage would not cause harmful interference to other systems. In the past, similar noncompliance usage has occurred [VUON]:

- The FCC in 1987, to promote the DBS service, allowed partial usage of the BSS Ku-band for FSS [FCC].

- The FCC allowed Qualcomm to use a FSS Ku-band transponder of a Gstar satellite for its OmniTracs service, which is MSS, on a non-interference basis (i.e., if harmful interference is detected, the service must be stopped) [NICH].

- Intelsat and COMSAT (not the ITU) allowed the Navy to use CSCI/Intelsat's FSS C-band global transponders on a non-interference and experimental basis for the Challenge Athena project, which is MSS [HEAR].

- Hughes Communication Inc. (HCI) (not the ITU) has also allowed DARO to use CSCI/HCI's FSS Ku-band SBS transponder on a non-interference and experimental basis for relay communication testing of its Unmanned Aerial Vehicles (UAVs), which is MSS [SMIT].

4.3.2 Service Coverage and Connection

One of the main reasons for LEO spacecraft to use NASA's relay communication services (instead of direct-to/from-ground communication) is for real-time or near real-time communication that requires full (or nearly full) geographic coverage to LEO spacecraft. NASA's TDRSS provides 100% coverage to LEO spacecraft with active GEO satellites located in the three ocean regions (Pacific, Atlantic, and Indian). TDRS's communication antennas do not provide wide beams. However, the beams can be steered to individual spacecraft mechanically (with Single-Access S and K-band reflector antennas) or electronically (with Multiple-Access phased-array helix antennas).

From orbital geometry considerations, to fully cover the earth, a LEO system (altitudes of up to 2,000 km) requires a constellation of around 40-70 satellites, a MEO system (altitudes of 8,000–20,000 km) 6-20 satellites, and a GEO system (excepting North and South Pole areas) 3–6 satellites [MAKI]. Antenna coverage must be practically as wide as line-of-sight coverage to provide full coverage.

To fully cover LEO spacecraft, the number of GEO and MEO satellites required may be the same or slightly greater. There is no coverage to LEO spacecraft from LEO systems that use earth-pointing antennas if the altitude of the LEO spacecraft is higher than that of the LEO satellites. For example, Teledesic, in its latest version, will operate at about 10,000 km, which, according to our mission database, Section 2.5.5, is higher than about 70% of NASA missions. Iridium, at 780 km, would cover no more than 35% of missions with its earth-pointing antennas. For LEO systems that use ISLs, e.g., Iridium, and in the future, Teledesic, coverage to LEO spacecraft is theoretically possible via these ISLs. However, in practice, the ISLs are designed for internal network signaling and call/data routing and cannot be used to provide communications service with LEO spacecraft. Most other commercial systems are not equipped with ISLs.

Note that even a LEO spacecraft located within the service coverage area of a commercial satellite system, because of its fast movement, may not be able to connect to the system. Because these systems, particularly FSS systems like Teledesic, may not be able to locate a fast-moving, high-altitude terminal, they may not be able to properly assign satellites or beams to serve the terminal. This positioning problem may occur with LEO or MEO systems or any systems that use spot beams (fixed, steered, or hopped). GEO systems that use wide beams, e.g., Intelsat C-band global beams, do not encounter the positioning problem. The TDRSS is a GEO system that uses spot beams, but these beams are designed with the capability of tracking LEO spacecraft.

NASA GSFC conducted a coverage assessment of Ka-band alternatives to TDRSS service [YOUN]. Teledesic and Iridium's orbital parameters and RF frequency parameters from their

FCC filings were used. The coverage addressed in the assessment, however, is only line-of-sight coverage as the assessment did not take into consideration the antenna configurations and patterns of these systems. Iridium is an L/S-band system with its ISLs operated at Ka-band (see Section 3.1), so treating it as a Ka-band system is not realistic.

4.3.3 Doppler Effects

Doppler effects are changes (drift, shift) in carrier frequency at the receiver due to movement of the receiver relative to the transmitter. This frequency change must be accounted for in the design and operation of the system that provides the communication link. Improper account of the Doppler effects may cause the carrier to drift to adjacent channels causing harmful interference to the adjacent channels and also to the carrier itself. It may also cause the carrier recovery circuit of the demodulator to fail to properly track or even detect the presence of the carrier.

For the commercial leased transponder service class, the user designs his own link together with the transmit and receive terminals to take into account the Doppler effects.

For the commercial off-the-shelf service class, the service providers have already designed the links and the systems (i.e., the satellites, the transmit terminals, and the receive terminals). Most of the commercial off-the-shelf services can tolerate the movement of terminals placed on an automobile or a ship. Some, such as Inmarsat-Aero-C, can even provide services to airplanes. Some incorporate techniques to alleviate the Doppler effects. For example, the Inmarsat services use reference carriers for real-time measurements and then compensate for the Doppler frequency shifts.

It is not clear whether any of the candidate off-the-shelf services can tolerate the much higher Doppler effects associated with the NASA LEO spacecraft without modification of the associated off-the-shelf terminals. This would require an investigation into proprietary details of the vendors' designs.

The following provides a general analysis of the Doppler effects. Detailed and specific Doppler effect analysis would require further analysis. By assuming that the earth is round (with a radius R_e of 6370 km) and that the spacecraft circulates the earth due to solely the earth's gravitational force, then the (radial) velocity V and the orbital period T can be calculated simply from the following equations as functions of the spacecraft altitude H:

$$V^2 = G*M/(R_e + H),$$

$$T = 2*\pi*(R_e + H)/V.$$

Where M is the earth mass ($5.98*10^{24}$ kg) and G is the gravitational constant ($6.67*10^{-11}$ Nm^2/kg^2). At the geostationary orbit, H is about 36000 km, so from the formulae, the radial velocity is around 11050 km/hr, while at H = 200 km, V is increased to around 28050 km/hr.

Note that, typically, an airplane travels at a velocity of around 500 km/hr relative to the rotation of the earth. That is, its velocity is around 2220 km/hr (for eastward travel) or around 1220 km/hr (for westward travel).

Note also that once the velocities and locations of the satellite and the NASA spacecraft are known, the Doppler frequency shift Δf_d can simply be calculated from the following equation:

$$\Delta f_d = [\pm V_x*COS(\theta_x) \pm V_y*COS(\theta_y)]/\lambda = [\pm V_x*COS(\theta_x) \pm V_y*COS(\theta_y)]*f/C.$$

Where f is the transmit RF frequency, C is the speed of the light (300,000 km/s), V_x is the velocity of the satellite at the direction which forms an angle θ_x with the propagation direction (direction that connects the satellite to the LEO spacecraft), and V_y is the velocity of the NASA spacecraft at the direction that forms an angle θ_y with the propagation direction. In the above equation, the "+" or "−" sign is used depending on whether the satellite or the spacecraft travels with or against the propagation direction, respectively.

Note from the equation above that the Doppler frequency shift is proportional to the RF carrier frequency f. That is, the Doppler frequency shift is about 11 or 12 times more at Ka-band (forward: 22.55–23.55 GHz, return: 25.25–27.50 GHz) than at S-band (forward: 2020.4–2123.3 MHz; return: 2200.0–2300.0 MHz).

Note also that as the spacecraft moves, θ_y changes (and V_y may also change as the orbit may not be completely circular), thus the Doppler frequency shift changes. NASA GSFC has developed a computer program called Configurable Analysis Graphical Environment that performs Doppler shift analysis, among others, with respect to a given constellation of commercial satellites and a given orbit of a NASA LEO spacecraft [YOUN]. From [YOUN], the Doppler frequency shifts and the maximum Doppler frequency change rate associated with the Ka-band Teledesic system (assuming 288 satellites, altitude of 1,350 km, inclination of around 98 degrees) and typical LEO spacecraft (altitude of 300–700 km and inclination of 28–98 degrees) are around 870 to 970 kHz and around 15 to 30 kHz/s, respectively.

4.4 Specific Assessment

A specific assessment of the candidate commercial satellite communication services for possible usage by NASA to serve its LEO missions is presented below and in Table 4.4.

4.4.1 Little LEO Services (Orbcomm)

All of the three issues (ITU compliance, Doppler effects, and coverage/connection) addressed in Section 4.3 must be resolved before NASA can use the little LEO services for its relay communication services to its user LEO spacecraft. It requires further analysis to determine whether the issues are resolvable in a cost-effective manner.

The advantages of Orbcomm's services are that they are available now, with limited gateway stations, and are off-the-shelf services.

The disadvantage, however, is its low bit rates (2.4/4.8 kbps) that may only be used to provide command and telemetry services and possibly very limited mission data download.

Table 4.4 Assessment of Candidate Commercial Satellite Communication Services

	Little LEO (Orbcomm)	Big LEO (Iridium)	Big MEO (ICO)	L-Band GEO (Inmarsat)	Multimedia LEO (Teledesic)	Multimedia GEO (Spaceway)	Leased Transponder (Intelsat C-Band)
Advantages	– Off the shelf – Connection to public networks – Available now	– Off the shelf – Connection to public networks – Direct terminal-terminal conn. – Available now	– Off the shelf – Connection to public networks	– Off the shelf – Connection to public networks – Available now	– Off the shelf – High bit rate – IP-based – Direct terminal-terminal conn.	– Off the shelf – High bit rate – IP-based – Direct terminal-terminal conn.	– Tailored to NASA's requirements
Disadvantages	– Low data rate	– Low data rate	– Low data rate	– Low/medium data rate			– Not off-the-shelf (high startup cost)
Issues	– ITU compliance – Doppler effects – Coverage/conn	– ITU compliance – Doppler effects – Coverage/conn	– ITU compliance – Doppler effects – Coverage/conn	– ITU compliance – Doppler effects	– ITU compliance – Doppler effects – Coverage/conn	– ITU compliance – Doppler effects – Coverage/conn	– ITU compliance
Further Investigation	No	No	Maybe	Yes	Maybe	No	Yes

4.4.2 Big LEO Services (Iridium)

Iridium has ceased providing service since this assessment was done. Iridium has practically the same assessment as Orbcomm. It provided voice communication, which is not relevant here. The slight edge that Iridium had over Orbcomm was that it allowed direct terminal-to-terminal connection.

4.4.3 Big MEO Services (ICO)

The assessment of ICO's services is almost the same as for Orbcomm, except that ICO's satellites are in MEOs that probably do not have a coverage problem but still have the connection problem. However, during the course of this study, ICO declared bankruptcy.

4.4.4 L-Band GEO Services (Inmarsat)

Coverage and connection is not an issue with Inmarsat's services because Inmarsat uses GEO satellites and provides services with global (line-of-sight) beams. The Doppler effects issue is not as severe, as the use of GEO satellites reduces the relative velocity of the transmitter and receiver, and the system has inherent Doppler effect compensation. With proper enhancement in the design of Inmarsat-Aero terminals and services, the Doppler effects can likely be resolved. Other advantages are that the services have been available for many years and the maximum bit rates are much higher than those provided by the services of the little LEO, big LEO, and big MEO.

4.4.5 Multimedia LEO Services (Teledesic)

The great advantages of Teledesic's services are: i) very high bit rates, up to 64 Mbps per terminal, meeting practically all LEO mission data rate requirements; ii) IP-based in accordance with future IOA requirements; and, iii) direct terminal-terminal connection that eliminates back-haul links or double-hop links.

However, Teledesic's services have all of the three issues that were addressed in Section 4.3. It is not clear whether the Doppler effects issue and the coverage/connection issue can be resolved. The Teledesic design is very fluid at this point, so there is no way to address the feasibility issues in detail. It is also highly doubtful that Teledesic will be deployed in this decade.

4.4.6 Multimedia GEO Services (Spaceway, Astrolink)

Spaceway and Astrolink's services are broadband and IP-based just like Teledesic. However, they provide only partial earth coverage, even with a full deployment of the system.

4.4.7 Leased Transponder Services (Intelsat)

Coverage and connection is not an issue with the leased transponder service using Intelsat's global C-band transponders. Through proper design, the Doppler effects issue can be resolved. The ITU issue may also be resolved through operation on a "non-interference" basis (see Section 4.3.1). The services can be tailored to meet NASA's requirements (e.g., bit rates and IP-based).

The disadvantages, however, are design and development cost and start-up cost (e.g., cost of the three ground stations). Because Intelsat's global C-band transponders are a hot commodity, there may be an issue of availability of these transponders at the three ocean regions.

4.4.8 Summary of Specific Assessment

Based on the assessment provided above, it can be concluded that:

- Little LEO (Orbcomm), big LEO, and big MEO (ICO) services are less suitable and have more issues to be resolved than the Inmarsat services. The big LEO and MEO systems also do not appear to be commercially viable. Multimedia GEO (Spaceway) services meet NASA's bandwidth requirements but not the global coverage requirements.

- Inmarsat-Aero services can be used to serve NASA's LEO missions that require low bit rates (64 kbps or less). However, enhancement of the Inmarsat Aero terminals may be required to accommodate the faster movement of the LEO spacecraft.

- Teledesic's services are IP-based and broadband, but interoperability with NASA missions involves significant regulatory and technical problems. It is also unclear that Teledesic will be deployed.

- Leased transponder services using Intelsat's global C-band transponders can be used to design satellite links and earth stations tailored to NASA's requirements. There are issues of cost, transponder availability, and regulation.

4.5 Protocol Interoperability

In this section, issues arising from the IOA requirement to interface near-earth mission spacecraft to terrestrial IP internets are discussed. The focus is on IP and associated protocols.

4.5.1 IP Interoperability

Protocol for satellite transmission is a very broad topic, exhaustively investigated by researchers in academia, in NASA, and in private industry. It is not our intention to review this literature or propose solutions for the IOA. Rather, this section shows by selected examples how protocol issues affect the system design, which in turn will drive decisions on the technology components that will be needed. The discussion assumes near-earth missions.

The IOA proposes IP as the network layer standard throughout the NASA IOA Intranet. However, terrestrial IP networks were not designed for the kind of network needed for NASA's space-to-ground communications. The problem stems from the fact that LEO/MEO spacecraft are moving with respect to the terrestrial network. This means that, in general, the network topology and geometry are constantly changing. Within IP, the problem lies in the route propagation protocols. These are the algorithms and associated messaging protocols that keep the routers informed of the current configuration of the network to the extent necessary to keep their routing tables up to date. These protocols were designed to automate the process of changing routing tables due to additions, deletions, and faults in networks, links, and hosts. Though terrestrial networks are dynamic in this sense, the time scale of change is much slower than for the LEO/ MEO connectivity changes. The route propagation protocols were not designed for this rate of change, so they may propagate change information too slowly to keep up. Also, at a higher rate of change, the network may become heavily loaded with traffic from these protocols. The usefulness of the standard algorithms in the space-to-ground part of NASA's intranet will depend on such parameters as the network topology and the number of nodes. In this section we briefly as-

sess alternative approaches for an IP network with mobile nodes. At this point we leave open the issue as to whether the mobile nodes are routers or hosts. The most common approach to handling mobile hosts is dial-up access. This approach bypasses the problem of changing routes. A link is established to a home router through a circuit-switched network. Routes do not change because the mobile host always appears to the home router to be on the same link.

If it is desired to have a true mobile IP network without making use of an intervening circuit switched network, it will be necessary to investigate the route propagation protocols. It may be necessary to substitute a new protocol in the space-to-ground part of the network. This would probably require partitioning the network into a portion running standard protocols and a portion running the new protocol.

Fortunately, the interoperability of two networks running different route propagation protocols should not be a problem. This is a common situation in internets. In internet terminology there is an entity called an autonomous system (AS), which is a network or set of networks under a single administrative authority. Within a given AS, the administrative authority is responsible for assuring that a routing propagation protocol is uniformly employed throughout. Within an AS, the protocols that are typically used are Routing Information Protocol (RIP) and Open Shortest Path First (OSPF). Between ASs a different protocol is used, Border Gateway Protocol (BGP). BGP essentially solves the problem of interoperation between two ASs with differing route protocols since the protocols within each AS are hidden and isolated from the outside world. This scheme implies that if the space-to-ground part of the network needs a special or modified protocol, it should be segmented from the rest of the network as a single AS. The simplest design is a single route connecting the AS to the rest of the intranet and a single router as the gateway.

Within an AS dedicated to the space-ground interface, it may be possible to use RIP or OSFP, depending on the complexity of the network. RIP is a vector-distance protocol. The vector is the IP address of a network. The distance is the number of hops (routers) to reach that network. Route information is propagated by each router advertising its routing table every 30 seconds to the routers immediately connected to it. In a rapidly changing network, and even in an ordinary network, problems can occur such as the creation of loops, instabilities, and slow convergence in which inconsistencies among routers arise. These problems can be mitigated in very small or simple networks, but in a complex, fast-changing network, the routers will not converge, and the protocol simply breaks down.

OSFP is a type of link-state or shortest-path-first protocol. In this type of protocol, each router has information on the complete network topology. This protocol tests the link status, either up or down, with the routers that are its immediate neighbors (as does RIP) and periodically broadcasts the link status information to all routers. The network topology is used by each router to calculate the shortest path using the Dijkstra algorithm. Because routes are calculated locally, the computation is guaranteed to converge. OSPF also functions independently of the number of routers and networks. The relative merits of OSFP with respect to RIP could best be determined by simulation [COME].

A simple network, in Figure 4-1, illustrates how the network design details affect the protocol performance.
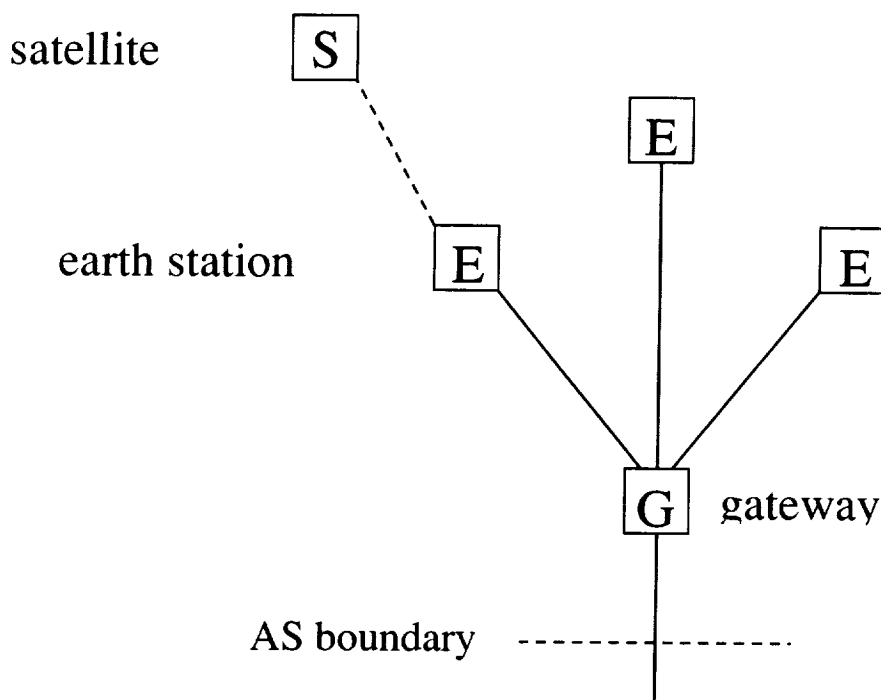
Figure 4-1 Simple Space-to-Ground Network

The earth stations are all connected to a common router that is the gateway to the space-to-ground AS. Mission platforms connect to different earth stations at different times. We show one platform connected to one of the earth stations. The active routes are S to E to G. Routes E to G to E would not be needed. A change in the status of the link S to E only has a short distance to propagate, one or two hops, so the needed routes should propagate quickly. An actual network design will probably be more complex when other requirements are taken into consideration, such as the need for redundant routes and routers. An additional source of complexity would arise if ISLs are introduced. For such more complex networks, new route propagation protocols may be needed. Some candidate protocols are cited in [PRAT]. This paper discusses protocols that might be suited to a complex space network such as Iridium. The protocols discussed are Extended Bellman-Ford and Darting. Extended Bellman-Ford uses special procedures that reduce the convergence time in the presence of loops. Darting is an algorithm that was designed to minimize overhead message traffic in a rapidly changing network. It does this by only sending topology change information when a data packet is sent and encapsulates the change information in the data packet. The protocols were simulated, and Extended Bellman-Ford was found to have superior performance to the Darting approach.

Mobile IP [IETF] is an approach to networks with mobile hosts. Without reviewing how this functions, we note only that much of the functionality is devoted to the mobile host acquiring a "care-of address," its temporary roaming address, and then informing the home agent (at the home address) of its care-of address. In a satellite network this would not be the most efficient

approach since the satellite locations are predictable, so the home agent really only needs to know the orbital track.

[ERNS] is an interesting proposal for a completely different approach that would introduce spatial location information into the IP addressing scheme itself. It would require a larger address space such as in IPv6, with one part of the address being permanent and the other part containing a position coordinate. It would use the domain name service (DNS) to propagate changing address information. One technical problem with this scheme is that position information is needed for all devices in the system. The author proposes GPS to provide this, but GPS will not work for mobile devices indoors. On the other hand, this would not be a problem for NASA satellites.

4.5.2 TCP Interoperability

There has been a great deal of research into the problems of TCP over GEO satellite links. Without reviewing this extensive literature, we will briefly discuss its relevance to the IOA problem.

An example of a problem is the bandwidth-delay problem. TCP contains a buffer called a window that is configured to 8 kilobytes in most standard applications. For a given propagation delay, this window size limits the bandwidth that can be achieved. The limitation is quite severe for longer propagation delays such as are experienced in a GEO satellite link. The achievable bandwidth is the window size divided by the delay, 500 milliseconds, or 128 kbps (per TCP connection). To get higher bandwidths, the window size must be increased. Changing configuration parameters such as this is sometimes called "tuning" TCP.

It can be argued that TCP, as a generalized protocol, can handle virtually any network environment by proper tuning of its parameters. The problem is that TCP exists both as a generalized protocol and as a specific instance of the protocol as deployed throughout the Internet. This latter form, the "standard" TCP as used commercially, is one in which the parameters are tuned to a standard setting. This is because TCP is an end-to-end protocol, so all the clients and servers in the network must be reasonably matched. For practical purposes, then, TCP with adjusted parameters, such as increased window size, is essentially a new protocol. This is even more the case for modifications such as modified acknowledgement schemes and modified slow-start congestion algorithms.

There are many schools of thought on how to deploy TCP in a GEO space relay environment. At one end of the opinion spectrum, some GEO network providers claim that they have no problems with unadjusted TCP. For example, Jon Masey of Interpacket Group, Inc., says that the ping time of 550 milliseconds via satellite to Africa and South America is actually less than for the terrestrial route [BROW]. Some applications such as transaction processing using Oracle will perform very poorly, however. More generally, there is agreement that some modification of TCP is required, or a different protocol should be used in the satellite link. As we have suggested, however, a modified TCP is essentially a different protocol.

A presentation by Mentat, the maker of a TCP gateway product for GEO applications, surveyed the solutions for TCP problems for GEO links [IVSC]. They are listed below with some of Mentat's conclusions:

- Increased FEC: Does not solve all TCP problems

- Data caching: Saves bandwidth but doesn't solve TCP problems

- TCP parameter changes: Requires modified TCP stack on all clients and servers

- TCP algorithm improvements: Difficult to make compatible with installed base

- LEO/MEO satellites: Solves some TCP problems but variable RTT is a problem

- End-to-end satellite protocol: Only feasible for self-contained satellite networks

- Spoofing: Not safe to use, will break applications

- Protocol gateways: Works if end-to-end semantics are not broken

Mentat's recommended solution is their gateway software product. It claims that its gateway does not break the end-to-end semantics of TCP. This is an essential feature of any such solution.

Not all the solutions for the GEO space environment are relevant to the IOA's near-earth mission services. The bandwidth-delay problem that exists for TCP in GEO environments will not necessarily be a problem for near-earth NASA missions. It would not be a problem for direct data downlinks but would be for relay to GEO data relay satellites. But there are other problems with TCP that exist in the LEO/MEO environment as well, such as the error characteristics of the RF channel and variable RTTs. The gateway solution should also work for LEO spacecraft, but this requires further investigation.

There is another basic problem for TCP-based applications in the LEO mobile environment. Since satellites will be visible to ground stations only within a limited time window, TCP connections with the satellite will be established and broken accordingly. If there is no process that keeps track of the time limits of the satellite visibility with respect to the ground station, the connections will be broken in an unscheduled manner. Applications such as FTP will simply terminate without having completed the file transfer.

This suggests that either special applications or special management layers ("middleware") above the TCP layer will have to be used at both the client and server ends, which transparently handle the satellite visibility issue, or human clients will not directly connect to the mission spacecraft. If the TCP connections are not direct, they would instead exist only between clients and a spacecraft home server. In this architecture, a spacecraft would autonomously download data to its home server when connected to a ground station. These considerations illustrate that the mobile nature of the network is a significant departure from the standard TCP environment and introduces several systems engineering issues that must be addressed.

4.5.3 Security

Traditionally, security has been an afterthought in the design of networks, but there is now increasing awareness that security is a major system design driver. Security may have unexpected architectural implications. The Internet is heterogeneous, distributed, and ad hoc, with most of the complexity at the edge. This philosophy is attractive since systems can be added and changed without the need to go through a central authority. Unfortunately, security drives the architecture back toward the old centralized, bureaucratic paradigm. If the network is to be managed from a consolidated operations center, security standards will likely be imposed uniformly across the network. This includes major security areas such as access control, authentication, event audit-

ing, intrusion monitoring, firewall policies, key distribution, and configuration control. These functions may have their own centrally managed servers.

An example of a security requirement that is sometimes desired by security engineers and that affects the network design is the requirement for static routing in the private network. Static routing uses fixed routing tables that are manually updated when a change is made. Static routing affords the security manager a means of controlling the network configuration. All changes must go through a central authority. Of course, static routing is incompatible with the dynamic LEO network connectivity. It is also incompatible with the concept of automated network management, which protocols such as RIP and OSPF were designed to support.

Security extends all the way to the spacecraft, so the system security design drives the security functions that must reside on the spacecraft. For example, encryption can be applied at the link layer, the network layer, or the application layer. Any or all of these may be employed in the network design. An example of application layer encryption is file encryption, which is used to protect the confidentiality of the content.

Encryption is used to prevent intrusion as well as to protect content. For example, network layer encryption may be used in the wide area network to protect intrusion into the private network, while also protecting content. Similarly, link layer encryption may be used in the forward/ground-to-space link to prevent spoofing of the RF protocol. This is accomplished by the fact that the spacecraft only recognizes messages that successfully pass through the onboard decryption process. Messages originating from unauthorized sources will not pass through.

Any or all of the above may be required by the security architecture. Since encryption protocols require processing at both ends, any of the above may be required on board the spacecraft, along with their associated key distribution protocols. This suggests the need for a powerful, programmable processor onboard the space platform, capable of incorporating encryption functions.

5. TECHNOLOGY ASSESSMENT

Specific technical and technology areas that need solutions are investigated for a set of "cases." The cases are realistic system concepts for the LEO-to-ground communications part of the IOA.

5.1 Definition of Case Studies

Based on the assessments performed in Sections 3 and 4, we have hypothesized the following system concepts (cases):

- Case 1. Inmarsat global relay network for long-duration balloons and aircraft
- Case 2. Inmarsat global relay network for LEO/MEO spacecraft
- Case 3. Commercial Ka-band direct link network for LEO/MEO spacecraft
- Case 4. Commercial Ka-band data relay for LEO/MEO spacecraft
- Case 5. Optical data relay system for LEO/MEO spacecraft

The cases are roughly mapped to the IOA-defined time frames, indicating relative technological maturity, as follows:

- Near term implementations (1999–2002): Case 1.
- Transition term implementations (2001–2003): Case 2.
- Far term implementations (2004–2008): Cases 3, 4, 5.

5.2 Case 1. L-Band Global Relay Network for Airborne Platforms

Commercially available Inmarsat transceivers designed for aircraft communication are suitable for NASA science missions carried on many types of airborne platforms.

5.2.1 System Concept

The concept is for command, telemetry, and instrument data from NASA airborne platforms to be relayed to NASA gateways using COTS Inmarsat transceivers (terminals) that are designed for airborne applications. The system would use one of the Inmarsat Aero services, such as the Aero Mini-M service. The only component purchased by NASA would be the platform transceiver. The service would be fully commercial, off-the-shelf, and "on-demand."

The Inmarsat Aero services provide global narrowband coverage. The satellites have global beams, while the newer Inmarsat 3 series also have spot beams to allow for low gain, smaller airborne terminals.

The main components of the system are:

- Mission Platform: COTS flight-qualified L-band transceiver
- Relay Satellite: Provided by Inmarsat service
- Earth Station: Provided by Inmarsat service

5.2.2 Current Technology

Inmarsat supports aeronautical communications, either single channel or multichannel, including voice, packet mode data up to 10.5 kbps, fax, and circuit mode data up to 4.8 kbps.

There are currently 6 services supported [INMA]:

- Aero-L (low gain): 600 bps data.

- Aero-I (intermediate gain): Interfaces to high-EIRP, spot-beam Inmarsat-3 satellites. Allows for lighter weight terminals. Circuit mode only in the spot beams.

- Aero-H (high gain): 10.5 kbps data, voice, and fax.

- Aero-H+: Same as Aero-H but capable of interfacing to Inmarsat-3 spot beams.

- Aero-C: Low data rate, low duty cycle store, and forward messaging.

- Aero-Mini-M: Aeronautical version of Mini-M service. Supports small, lightweight terminals. The service provides the same capabilities as Aero H, H+, and I.

The state of the art in terminals is represented by the new Aero Mini-M terminals such as the Honeywell/Racal SCS-1000. It is a single channel radio with a self-contained tracking antenna unit [HONE].

5.2.3 Technology Projection

The outlook for other commercial satellite systems serving the aeronautical market is highly uncertain since the bankruptcy of Iridium and ICO. Globalstar is now showing signs of failing to meet marketing goals. Inmarsat has a proven track record of providing narrowband service to the aeronautical market and is committed to continuing that service with the future launch of its Inmarsat 4 series satellites. The Inmarsat 4 satellites will be service-compatible with the previous generation satellites.

5.2.4 Outstanding Technical Issues

The Inmarsat approach is considered to be a completely COTS solution for airborne platforms. However, for extremely high altitude aircraft and balloons, the altitude, temperature, and pressure requirements for the specific mission may exceed the specifications for the transceiver unit.

Because the bandwidth of this service is limited, there would not be a bandwidth-delay product problem for TCP, as discussed in Section 4.6.2. There would be a "mobile IP" problem unless the mission platform uses the "dial-up" approach to access the NASA gateway.

Because the platforms are relatively slow-moving, they will remain within the coverage zone of a single satellite in most cases. However for circumnavigating missions, a platform will pass through different coverage zones. There is a handover problem when the platform passes from one satellite's coverage zone to another. This must be handled by a special protocol, yet to be designed. At a minimum, a means of limiting the session duration to the time in a single beam must be provided. This would involve predicting the time when the connection needs to be terminated as the boundary of the coverage zone is reached and shutting down all applications at that time. This handover function would then reconnect to the next Inmarsat satellite and start up the applications again. For sounding rocket platforms, the Doppler shift may be outside the

Doppler tracking capability of the COTS terminals. The cost of Inmarsat service may be an issue. The usage charge is $7 per minute, maximum to as low as $1 per minute for high usage customers. The cost of the Aero transceiver is approximately $300,000, including installation and check-out in the aircraft.

5.3 Case 2. L-Band Global Network for LEO Platforms

5.3.1 System Concept

The concept is to provide global communications coverage along with limited science telemetry return data for NASA LEO spacecraft via Inmarsat's commercial GEO relay satellite service. This would be a global, full duplex, digital, packetized, on-demand service. Data rates could be up to 64 kbps. This would be a new service, perhaps to be called "Inmarsat LEO." Data would be relayed via Inmarsat satellites to Inmarsat land earth stations (LES), to a commercial ground network, and on to a NASA gateway.

The concept is based on modifying a COTS Inmarsat terminal for operation in space and in the presence of high carrier frequency Doppler shift.

The main system components are:

- Mission Platform: Space-qualified L-band transceiver with tracking antenna
- Relay Satellite: Provided by Inmarsat
- Earth Station: Provided by Inmarsat

5.3.2 Current Technology

In Section 4, Inmarsat was identified as a viable candidate for providing global digital wireless communications to NASA LEO spacecraft. The concept relies on the assumption that a COTS Inmarsat terminal may be modified to operate in the LEO environment since no such device currently exists off the shelf. Further investigation revealed that the feasibility of this concept has already been tested in space by Spacehab, Inc. [SHAB].

Discussions with Comsat Mobile Communications (CMC), the U.S. signatory to the Inmarsat Consortium, and Spacehab, Inc., integrator of the Inmarsat communications experiment carried on STS-91, indicated that there are no technical obstacles to modifying a COTS terminal to interface to Inmarsat. In fact, this was the goal of the Spacehab Universal Communications System (SHUCS) experiment.

The SHUCS experiment was funded by Spacehab, starting in 1995, and culminating in a flight test onboard STS-91 in June 1998. The SHUCS experiment used an L3 Communications Lynxx, a portable terminal designed for use from a stationary position; that is, the antenna is non-tracking. Spacehab modified the terminal by adding a tracking capability to the antenna and Doppler compensation software in the terminal itself. The method chosen for acquiring and tracking the Inmarsat satellite was based on GPS and included an inertial reference unit to compensate for short-term attitude changes by the STS platform. Inmarsat made special provisions during the experiment, such as providing extra channels as guard bands for the Doppler excursions that could be expected.

Due to various technical problems, the experiment was only a partial success but demonstrated that the concept is sound. One important result was that the GPS acquisition and tracking method chosen did not allow the system to acquire quickly enough. Spacehab has decided to use a different type of terminal for its next test, one designed for aeronautical platforms with a tracking antenna.

Spacehab's goal for future development is to provide a SHUCS-based on-demand service for STS payloads, for the ISS, and for any other customers that may find it useful. Some features of the proposed service that are stated by Spacehab are [SHAB]:

- Global coverage
- Voice service with encryption option
- Data service, 64 kbps, 16 kbps, and 9.6 kbps
- User interfaces: DTMF telephone, RS232, RS422/449, V.35, and 10BaseT
- Round trip latency: 0.7 seconds
- Satellite coverage zone handover: 30 seconds

Some of the relevant Inmarsat COTS products are mentioned below.

Canadian Marconi makes two L-band Inmarsat antenna systems for aircraft, a high gain electronically steered antenna (CMA-2102), and an intermediate gain unsteered antenna (CMA-2200). The communications hardware, other than the LNA, is not included and must be purchased from a supplier such as Honeywell or Rockwell. These are specified to 50,000 feet but could probably be upgraded to vacuum conditions. The costs are $75 K to $125 K, depending on quantity, for the steered antenna and one third of that for the unsteered antenna [MARC].

The state of the art in a Doppler-compensated airborne terminal is represented by the new Aero Mini-M terminals such as the Honeywell/Racal SCS-1000. It is a single channel radio with a self-contained tracking antenna unit. The antenna unit handles attitude control as well as tracking. The design minimizes size, weight, and power. However, it only operates with the Inmarsat-3 spot beams [HONE].

Note that these airborne terminals are designed for the Inmarsat Aero services. The maximum data rate is 10.5 kbps per channel for the Aero services. The Case 2 concept would be a new service since it does not conform to the current Inmarsat standards.

5.3.3 Technology Projection

Spacehab appears to be committed to going forward with its SHUCS service. Since it is testing the system on its modules flown on the STS, the tests are few and far between. Funding is a limitation, and government investment would likely speed the process.

When Inmarsat upgrades to the Inmarsat 4 satellites, the global beams may no longer be available. Inmarsat 4 will use steered spot beams. While this will allow further reduction in size, weight, and power of the user terminals, it may create complex problems for fast-moving space platforms. The spot beam positioning and handover algorithms will be optimized for slower-moving land, sea, and air platforms and might not be able to accommodate spacecraft.

5.3.4 Technical and Technology Gaps

Several technical issues must be resolved to implement the Case 2 concept:

- Antenna pointing
- Signal tracking
- Doppler correction
- Network issues

Spacecraft Antenna Pointing

There are two ways to point the antenna at the communications satellite. One way is to locate the platform in space, both in position and attitude, then, using a prior knowledge of the location of the communications satellite, calculate and point the antenna at the communications satellite. This can be done, as demonstrated by Spacehab. This is a difficult operation, as also demonstrated by Spacehab. One needs a set of at least three GPS antennas and receivers, and an algorithm to accurately determine the direction of arrival of the GPS signals. Due to the increased precision required for attitude determination as compared to position determination, the time to acquire attitude is, theoretically, 1000 times as long as to acquire position. Lastly, the location of the communications satellite must be carried on board the platform. Communicating with a ground station directly simplifies the problem only in that the ground station does not move.

The second approach is to search for the communications satellite without any prior knowledge of its location or the platform's attitude. Besides defining the search algorithm, one determines that the correct satellite has been acquired and must account for the possibility that the platform may be in an inverted geometry; i.e., that the platform is able to see the satellite and is not upside down. In evaluating acquisition algorithms, we found that the antenna gain did not affect the time taken to acquire, if there were no Doppler. This is because a larger antenna gain reduces the dwell time at any location; the narrower beam requires a proportionally larger number of search positions to find the satellite. The inclusion of Doppler allows a higher gain antenna to acquire faster because the shorter dwell time permits fewer frequency trials over the Doppler range. An appropriate search algorithm would be a spiral search, to minimize the effect of movement, over beam positions similar to those of a geodesic dome. When the satellite is located, a helical scan could be continued for tracking, similar to that used in military aircraft radar target tracking.

Doppler determination can be accomplished by using orbit parameters or, more simply, by performing the acquisition procedure over the range of Doppler frequencies. This takes more time, but the total acquisition time need only be a few seconds.

A spreadsheet shown in Appendix B relates the system parameters to the acquisition time. An L-band 64 kbps signal, using a 0.9 m (20 dB of gain) antenna, with ±30 kHz of Doppler would take about 0.42 second to acquire the satellite and the Doppler. If the data rate is lowered to 9.6 kbps and the EIRP also lowered appropriately (8.2 dB), the acquisition time increases to 16 seconds even without any platform roll. If the platform is pitching at a rate of 2.3 degrees per second or if the combined platform pitch and the satellite movement results in the satellite having an apparent pitch rate of 2.3 degrees per second, the time increases to 34 seconds. However, if the

antenna scans were done for each Doppler frequency instead of doing the Doppler search within the scan, the acquisition time could be cut in half.

It would be most advantageous to use a phased array electronically steered antenna to achieve the acquisition times described. However, a mechanically steered antenna could be used if it could be steered very quickly, on the order of 1/100th of the acquisition time.

If the acquisition fails, the platform most likely is in an inappropriate attitude.

The most easily acquired signal is a continuous wave (CW) signal. This would be the satellite pilot signal, or a communications tone specially set up to initiate communications with the desired platform. A possible problem with this is that the search covers most of the sky (or earth, in the case of a direct to earth link), and there are many CW signal sources. A characteristic modulation should be applied to the signal, for example, a repeated short Barker code. The receiver must then have a matched filter, which would produce periodic impulses. These impulses would then be processed by a digital filter to measure the signal energy. The performance would be the same as by the tone detector.

If Ka band is used for direct communications with the ground, the ground station must also acquire and track the platform. All of the above discussion and calculations apply to this link and terminal as well.

There are at least two ways to do antenna tracking. The simplest is to use a spiral scan or a nutation of the antenna. When the signal level varies, the antenna is moved in the direction of the larger signal. The other more complex approach, which is used by Deskin, is to use an antenna with multiple feeds. Several receivers are used on sum and differences of the feeds, with correlators operating or these signals. When the sum and difference signals are uncorrelated, the antenna is pointed correctly. The sign and magnitude of the correlation tells which direction and how much to move the antenna.

Signal Tracking

In addition to the antenna tracking mentioned above, the receiver must also track the Doppler of the received signal. Data communications receivers must have a phase tracking loop to demodulate the data. This loop will provide for tracking the received Doppler and will also provide the Doppler value needed for the transmitter.

Doppler Correction

The Doppler frequency offset, ignoring relativistic effects, is proportional to the velocity times the frequency. This offset is measured by the receiver. The transmitter then must compensate by shifting the transmit frequency in the opposite direction multiplied by the ratio of the transmit frequency to the receive frequency. At L-Band, where the ratio is 16/15, the error introduced by taking the ratio as 1, would only cause a maximum error of 2 kHz, not enough to worry about. At this frequency, the transmit frequency could simply be translated by the receiver phase locked loop frequency.

However, at Ka-Band, considered in Case 3, where the ratio is 3/2 and the Doppler offset is much larger, the error could by as much as 300 kHz. Therefore, the Doppler would have to be measured and the transmit synthesizer adjusted.

For the direct to the ground system, transmit Doppler correction could be done on the ground.

Network and Protocol Issues

Since Inmarsat is a GEO system, the unique problems associated with GEO propagation delays will be encountered when TCP is used, as discussed in Section 4.6.2. However, because of the limited bandwidth per channel that is available through Inmarsat, the bandwidth limitations due to the TCP window size should not be significant.

Another potential protocol problem is that when the platform passes out of the coverage zone of one of the Inmarsat satellites, the link will be broken. Any TCP connections that exist will then be terminated in an unscheduled manner. A special handover protocol might be required for maintaining the TCP connections as the platform passes from one satellite coverage zone to the next. (In terrestrial wireless networks, for example, handover is accomplished at the link layer through the use of a control channel.)

Alternatively, the end of coverage could be predicted based on orbital data and all applications terminated in an orderly manner prior to that time. The special protocol that performs this function would then have to estimate file transfer times so that file transfers could be allotted sufficient time to be completed prior to the end of coverage. This protocol might reside between the application layer and TCP, for example, as an enhanced session layer.

5.4 Case 3. Ka-Band Direct-to-Ground Network

5.4.1 System Concepts

Case 3 addresses a direct link network for command, telemetry, and communication between a LEO mission spacecraft and the ground at Ka-band. Two system concepts are proposed for implementation of the direct link.

The first concept (System Concept 1, SC1) is for transmission of latency-tolerate information. SC1 is a direct outgrowth of the existing commercial TT&C services at L, S, and X-band currently provided to LEO spacecraft and GEO spacecraft by launch, spacecraft bus, or spacecraft payload manufacturers.

The second concept (System Concept 2, SC2) mitigates the latency problem. SC2 relies on the deployment of the satellite-based Ka-band broadband services, to be supplied by Spaceway [SPAC], Astrolink [ASTR], and Teledesic [TELE], for the required low cost Ka-band earth stations and components and on the maturity of IP technology for required delivery of IP packets to and from LEO mission spacecraft (discussed in Section 4.5). SC2 is meant to conform more closely with the concept of a miniature autonomous ground station described in the IOA.

Figure 5.4-1 displays the network architecture for SC1. The LEO mission spacecraft communicates with the SC1 earth stations whenever it is visible to them. The Network Operation and Data Distribution Center (NODC) is connected to the SC1 earth stations via backhaul links (satellite or terrestrial) and to the users via public networks (Internet, ISDN, and PSTN) or dedicated lines. The primary role of the NODC is to relay information to and from the LEO mission spacecraft, to control the network configuration (including the earth station's and spacecraft's), and to keep track of transmission transactions for billing purposes.
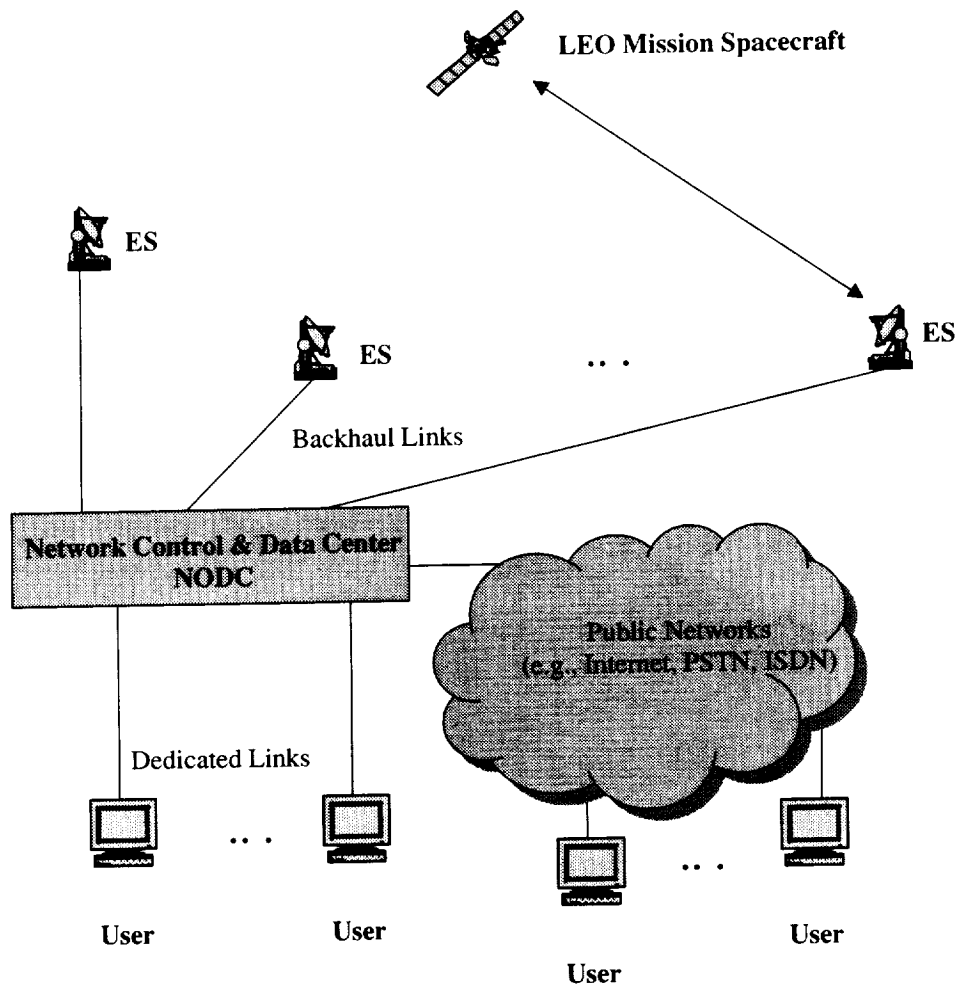
Figure 5.4-1 Network Architecture for System Concept 1

With SC1, typically only a few earth stations may be available. Accordingly, direct line-of-sight contact with the earth stations does not often take place, and data must be stored on the spacecraft and at the earth stations until it can be transmitted.

At Ka-band, the antennas of the spacecraft and earth stations are directional with pointing/ tracking capability to support high data-rate missions.

Figure 5.4-2 shows the network architecture for SC2. SC2 is different from SC1, in that:

- The earth stations are plentiful as in a VSAT network, distributed around the globe to provide greater coverage and approximate real-time access. (Data collected over an ocean may not be downloadable immediately to ground.) Accordingly, the earth stations are small and low cost.

- The earth stations are directly connected to a high-speed internet and act as routers.

- Each spacecraft has an IP address for routing purposes.

Figure 5.4-2 Network Architecture for System Concept 2

- Instead of a NODC to relay the data, there is a Network Control Center (NCC) to control the configuration of the spacecraft, the earth stations, the user terminals and other nodes within the network for real-time routing of packets, Quality of Service (QoS) guarantee, usage data for billing purposes, etc.

The features of SC1 and SC2 are summarized in Table 5.4-1.

Table 5.4-1 Characteristics of System Concepts 1 and 2

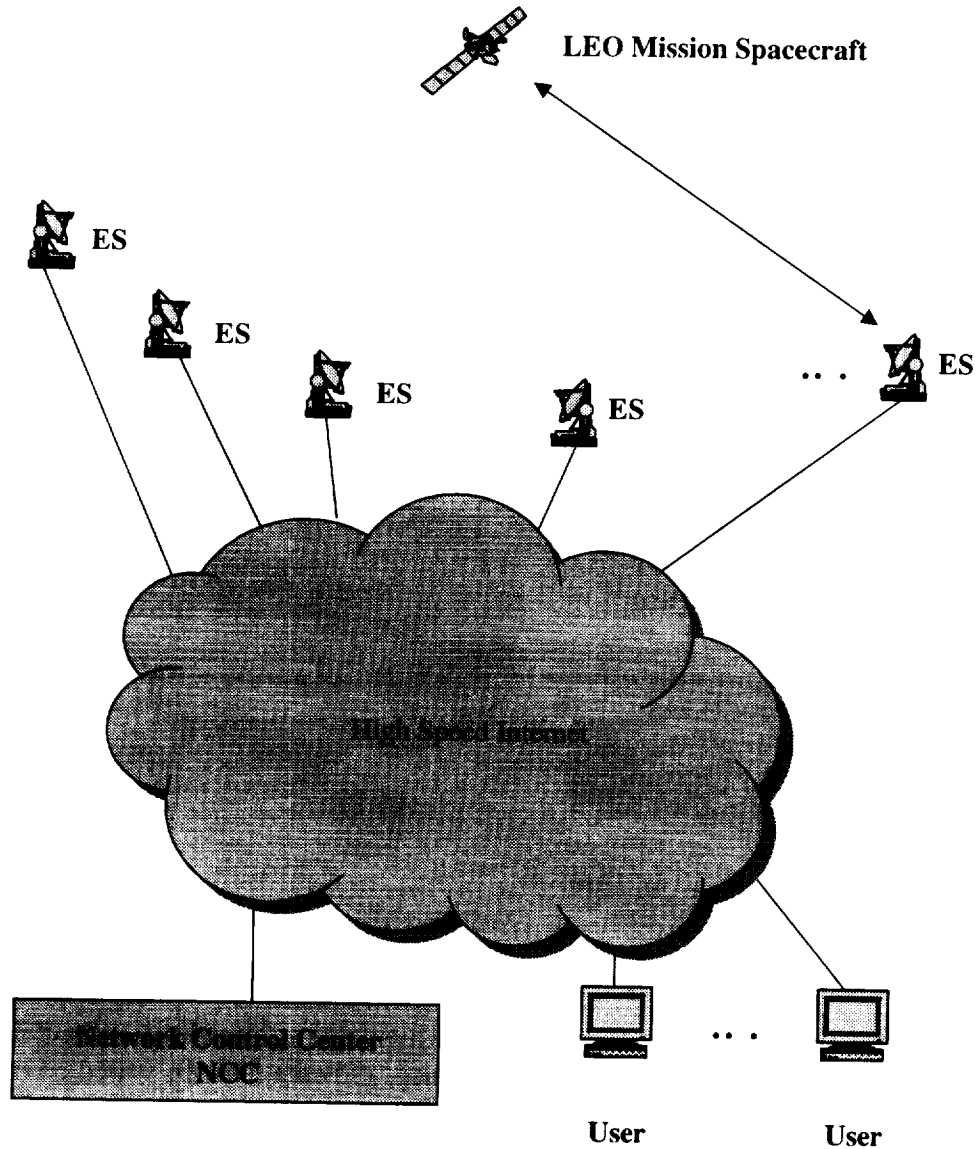|	System Concept 1	System Concept 2
Latency	Moderate	Low to Real-Time
Number of Earth Stations	<10	100s or 1000s
Earth Station Size/Cost	High	Low
Spacecraft RF Size/Cost	Low	Moderate
End-User Connection	Via NODC and Backhaul	Via IP Network
IP-Based	Maybe	Yes
Technology	Current	Near Future

5.4.2 Current Technology

LEO teleport services

To capitalize on the growing market for commercial "LEO-teleport" services, Allied Signal [ASTS] and Universal Space Network [USN] are building infrastructures similar to those shown in Figure 5.4-1. They have had customers at S-band uplink and X-band downlink (e.g., APL's FUSE and Navy's NEMO). They also plan to expand their infrastructures to provide Ka-band services to accommodate demands for high data rate transmission and NASA Ka-band require-ments. Table 5.4-2 summarizes characteristics of the LEO teleport services, as reported by Al-lied Signal and USN.

Table 5.4-2 Characteristics of LEO Teleport Services by Allied Signal and USN

	Allied Signal	Universal Space Network
Earth Station Name	LEO-T* or TAGS**	Not Specified
Earth Station Locations	Fairbanks, Alaska	North Pole, Alaska, South Point, Hawaii, and Horsham, Pennsylvania
Earth Station Sizes	13 m (fixed), transportable unspecified	3, 4, 5, and 11 m
Operating Frequencies	S-Band (UL), X-Band (DL), Ka-Band (?)	S-Band (UL), X-Band (DL), Ka-Band
NODC Locations	Washington, D.C.	Horsham, Pennsylvania, and Newport Beach, California
Backhaul Links	Not Specified	Not Specified
User-NODC Interface	Not Specified	Internet
Supporting Data Rate	Not Specified	150 Mbps, 600 Mbps (future)
Customers Supported	Navy's NEMO	APL's FUSE, LM/CSOC's TRIANA

* LEO-T: Low Earth Orbiter Terminal
** TAGS: Transportable Autonomous Ground Stations

Note that for support of polar missions, to optimize spacecraft visibility (duration and frequency), earth stations should be located as close to the poles as possible. This is probably why USN and Allied Signal have earth stations located in Alaska (North Pole and Fairbanks). Nevertheless,

there may be problems in designing the associated backhaul links when the earth stations are close to the poles. These problems will be addressed under Backhaul Links, below.

The Navy's Transportable Autonomous Ground Stations (TAGS) are transportable and mounted on the top of a vehicle.

Commercial Earth Stations

Deskin Research has made an antenna for Teledesic that tracks the platform by using a four quadrant feed. It must be pointed roughly at the platform to acquire the signal. Its marketing department indicated that each project is a custom job and the development would cost about $1 million, with additional units costing $500 to $700 thousand, in quantities of 10 [DESK].

Swedish Space Corporation makes small ground stations at L and S band for low orbiting satellites. Antenna size is between 0.8 and 2.5 m. The system tracks the satellite but apparently does not acquire it. The company did not provide technical information about performance or possible upgrades, including to Ka band, and did not provide a price [SSC].

Canadian Marconi makes a pair of L-band Inmarsat antenna systems for aircraft: a high gain, electrically steered antenna and a low gain unsteered antenna. The communications hardware, except for the LNA, is not included and must be purchased from an Inmarsat supplier such as Honeywell or Rockwell. The system is specified to 50,000 feet but could probably be upgraded to vacuum conditions. The costs are $75,000 to $125,000, depending on quantity, for the steered antenna and one third of that for the unsteered antenna [MARC].

Datron manufactures TV receivers and only antennas for vehicles, boats ($4,500), and aircraft ($100,000). These systems would require major redesign to make them transmit as well as receive and to make them track the platform signal rather than point to a fixed spot in the sky as they do now. However, Datron is building an S and X-Band system for NASA, Wallops Island, called LEO-T and is planning to build terminals for Teledesic. Datron is also open to special requirements systems, for a price, of course [DATR].

Aero Astro makes low cost spacecraft transceivers and ground stations for S and X band [AERO].

Stanford Telecommunications (Stel, now part of ITT) has a contract with NASA Goddard to build a small spread spectrum terminal using the multiple access mode of TDRSS. It has been tested on the ground at 150 kbps with a one watt HPA and a 0.5 m antenna. It will be space qualified. It presently does not track, but the company is developing a GPS based tracking approach.

Data Storage

Data storage onboard the spacecraft and on the ground is an essential requirement for the SC1. Space-qualified 224-Mbyte solid-state recorders are now available from SSR (in a separate document, *Satellite Communications Technology Database*). These recorders can be "daisy-chained" for extended storage. The Navy's NEMO spacecraft uses a 48-Gbit recorder [NEMO], and Landsat 7 uses a 380-Gbit recorder. Nanochip, Inc., [NANO] claims it will soon offer a 1.4-terabyte non-volatile, solid-state storage device in a 3-inch disk drive form factor.

Backhaul Links

Terrestrial backhaul services are available from telecommunication carriers (e.g., MCI World-Com) through their high-speed microwave and optical fiber networks. However, if earth stations are located in an extreme environment (e.g., near the poles), "last mile" connections may not be practically created.

Backhaul links may also be obtained by making use of the IP-based, FSS Ka-band satellite broadband services to be offered by Spaceway, Astrolink, and Teledesic.

Spaceway and Astrolink's services are planned to commence in the first quarter of 2003 via a constellation of several GEO FSS Ka-band onboard processing satellites (for each service) to serve most land mass areas south of 65°N latitude and north of 65°S latitude. Teledesic will provide truly global communication with its constellation of many LEO, or possibly MEO, FSS Ka-band onboard processing satellites. It was scheduled for service in 2004. However, it is believed that the development has been stopped for quite some time now. There are rumors that Teledesic would be used as a second generation Ka-band satellite system.

Each of these satellite services can be accessed through the use of its own COTS earth station via an Ethernet interface. That is, an IP frame (data with appropriate application header, TCP/UDP header and IP header) is segmented into an Ethernet packet for transmission to the COTS earth station. For reliable transmission over the air, an IP frame is broken up into small packets. Astrolink uses the ATM cell format, whereas Teledesic and Spaceway use their own packet formats. Each COTS earth station can support up to tens of megabits per second. If a higher data rate is required, multiple COTS earth stations can be used.

User-NODC Connection

According to SC1, a user needs to connect to the Network Operation and Data Center (NODC) to send command/communication data and to receive telemetry/communication data from the mission spacecraft. The user-NODC connection can be a dedicated line supplied by a telecommunication carrier (e.g., MCI WorldCom) or via a public network (e.g., PSTN, ISDN, or DSL) or the high-speed Internet services to be supplied by Spaceway, Astrolink, and Teledesic (see Section 5.4.3).

Pointing and Tracking

The antennas of the earth stations are required to have pointing and tracking capability. The pointing and tracking technologies were discussed in Case 2 (Section 5.3). The use of a Ka-Band frequency changes the parameters in the acquisition calculations presented there. The increase in path loss and antenna gain due to the use of a higher frequency tend to cancel out. However, because of the increased Doppler, a much higher EIRP is required, which implies a higher data rate. An example of a 1.5 MBPS link with a 0.9 M antenna is given in Appendix B. The acquisition time is a reasonable 1.6 sec.

Communication directly with the ground at Ka-Band would be similar. The EIRP and path loss would be different, but the data rate determines that ratio. Thus, the satellite acquisition time calculation spreadsheet, in Appendix B, can be used for direct to the ground acquisition by using the same data rate.

At Ka-Band, where the ratio of the transmit frequency to the receive frequency is 3/2 and the Doppler offset is much larger than in Case 2, the error could be as much as 300 kHz. Therefore the Doppler would have to be measured and the transmit synthesizer adjusted.

With mass production of directional earth stations for use with commercial LEO systems (e.g., Ka-band Teledesic), the cost of pointing and tracking equipment for use with SC1 and SC2 earth stations will be significantly reduced.

NASA, in collaboration with industry and universities, has also conducted studies and experiments with new technologies to reduce the weight and volume of pointing and tracking equipment, including antennas [NAS1 – NAS5]. Examples of these are several experiments and developments associated with the Direct Data Distribution (D3) project: the downlink MMIC Ka-band active transmit phased array antenna with low power consumption (265 W for a beam EIRP of 39 dBW), low weight (less than 2 kg), and low volume (800 cm^3) [NAS5]; the ferroelectric Ka-band reflectarray antenna (FRA) with tunable radiators for transmit and receive functions to reduce spacecraft mass and cost for the same antenna aperture [NAS3]; and a reconfigurable Ka-band antenna incorporating microelectro-mechanical actuators (MEMA) [NAS4].

Note that a phased array antenna, as compared to a reflector antenna, will not reduce antenna aperture size requirements for a given antenna gain/directivity. Due to the laws of physics, the phased array must actually be larger. Nevertheless, a phased array may have reduced volume. This is because its flatness and the size of the associated beam forming network should take less space than the mechanical motors and the support and space required for steering since phased array antennas required no extra space for steering.

Multiple Access

The earth stations can typically support multiple LEO mission spacecraft through space and time division multiplexing. It is possible but not likely that two or more spacecraft may get close to each other as seen from the earth station. To accommodate this case, it is necessary to use multiple earth stations or to use an earth station with multiple tracking antennas (one to track each spacecraft) and to use different frequencies for each link. Note that SC2 could make use of Teledesic type earth stations, which are equipped with two tracking antennas for continuous transmission. Note also that it is possible to track two spacecraft with multiple beams that are formed from a single phased array antenna. However, low-cost beam-forming networks with fine beam weight settings required for this type of tracking are not likely to be available in the foreseeable future.

Modulation and Coding

Low-cost high-speed (tens to hundreds Mbps) modems and codecs will be available with the launch of the satellite broadband Ka-band services from Spaceway, Astrolink, and Teledesic. They use QPSK with forward error correction coding of concatenation of two block codes or of a convolutional code and a Reed Solomon block code. Other implementations will use higher order modulations such as 16-QAM with concatenated trellis codes and Reed-Solomon codes, such as provided by Sicom, Inc.

Turbo codecs, now available on a chip [ECC], can be used to further reduce RF power requirements. Turbo coding was first introduced in 1993 [BERR] with a claim of achieving near the

Shannon limit. In the market today, turbo coding generally refers to Turbo Convolutional Coding (TCC) because they are built around the convolutional codes, as opposed to block codes, which are used for Turbo Product Coding (TPC) [AHA]. Using TCC at high code rates requires an extremely complex decoder. There are no known integrated circuits implementing TCC that perform close to the theoretical limits of the code [AHA]. On the other hand, recently, TPC has been implemented in a single chip by Advanced Hardware Architectures, Inc. [AHA] and Efficient Channel Coding, Inc. [ECC]. The performance of the TPC chip is at least 1.5 dB (or 40% in power) better than that of the state-of-the-art convolutional code concatenated with the Reed Solomon code [AHA].

Security

Data security is an important requirement. Authentication and integrity of data, particularly control or command signals, must be verifiable. Data must be kept private through encryption/decryption. It is a standard security problem to send private data over a public network (i.e., creating a virtual private network over the Internet). This standard security problem is still evolving, and its solution is still being looked at for improvement by network security engineers and scientists.

Encryption will produce ciphered text, typically with optimal entropy. Accordingly, if data compression is required, it must be performed before encryption. The IP security protocol standard IPSec/ESP is typically used in terrestrial IP networks where data are encrypted/decrypted between the IP and TCP layers. With the IPSec/ESP, the TCP/UDP header is encrypted, and accordingly, one cannot perform TCP spoofing to improve transmission throughput due to delay, traffic shaping to improve congestion, and Network Address Translation (NAT) required in dynamic routing. IETF has been working on modifying IPSec/ESP to accommodate long delay transmission (e.g., satellite transmission delay).

To perform encryption/decryption, the most popular algorithm, the NIST-validated Data Encryption Standard (DES) can be used. This algorithm (single DES), due to its short key length (56 bits) and Moore's Law, has been broken. For strong security, typically, the DES algorithm is applied repeatedly three times to form a triple DES with a key length of 192 bits (including parity bits), and keys are updated as often as practical. Later in 2000, NIST is planning to release a new version of the encryption standard to replace DES. It is called Advanced Encryption Standard (AES), which will operate with a key a few times longer than the single DES key. There is an issue that must be resolved with NSA on the export of encryption software and hardware that use long-length keys.

Ka-band Components

Ka-band technologies have been improved and matured partially due to the launches of the experimental satellites ITALSAT and ACTS and the development of experiments conducted with these satellites. In two or three years commercial Ka-band satellites (bent-pipe and processed) will be available for services with mass-production, low-cost Ka-band VSATs and components. A compilation of satellite communications technology research and development, mostly outside the United States, is summarized in a separate document entitled *Satellite Communications Technology Database* (SCTDB), NASA publication NASA/CR-2000-210563/Part 2.

For high power amplifiers (HPAs) for space applications, 140-W TWTA and 20-W SSPA have been developed (SCTDB). For ground applications, several SSPAs were developed using 0.15 to 0.25 micron pHEMT to provide a 1 to 2-W output power. The HPAs can be combined in phase to provide higher wattage. Combining results in gain ripple over frequencies that cause inter-symbol interference for high data rate transmission. Equalization may be required at the receive end to improve transmission performance. Techniques such as Multiple Carrier Modulation (MCM) or Orthogonal Frequency Division Multiplexing (OFDM) can also be used.

For low noise amplifiers (LNAs), a space-qualified pHEMT Ka-band LNA with a noise figure of 1.6 dB (i.e., 130 K noise temperature) was developed (SCTDB). From [LNR], for ground applications, HEMT Ka-band LNAs with noise temperature ranging from 100°K to 135°K and a gain of 45 dB minimum are available off-the-shelf. NASA is also conducting experiments to bring down the LNA noise temperature to 77°K [NAS2].

5.4.3 Technical and Technology Gaps

SC1 is for transmission of latency-tolerant information and is based on the current technologies. That is, there are no major technology gaps to implement the ground-based portion of SC1. This is evidenced by the fact that there are at least two companies, USN and Allied Signal, that are implementing the equivalent of SC1 to provide the LEO teleport services.

SC2 is for real-time or near real-time transmission of information. It uses small, low-cost ground terminals in accordance with the IOA. It relies on the deployment of the Astrolink, Spaceway, or Teledesic services for use (with modification) of their low-cost, mass-produced Ka-band VSATs and components. The deployment of the Astrolink and Spaceway services is scheduled in about 3 years. It is rumored that the development of the Teledesic system has been put on hold. It is not clear when the development will resume, if at all. As with SC1, there appear to be no technology gaps in the implementation of the ground-based portion of the system.

On the spacecraft side, the main item that needs to be developed is the spacecraft transceiver/ antenna. Whether or not this involves new technology could only be determined after a system architecture is developed in more detail. Taking into consideration the Ka-band projects that are already underway at NASA, at this point it appears that no new technology is needed. The phased array spacecraft antennas that are under development at Glenn Research Center and Goddard Space Flight Center might have to be modified. For example, they would have to be modified if a higher EIRP is needed or the frequency band selected is different from the ones for which they were designed. In addition, if the architecture that is eventually chosen requires an uplink also at Ka band, the antennas would have to be modified for full-duplex operation. Alternatively, if the uplink bandwidth is low, as indicated by our survey in Section 2, a separate low- to intermediate-gain receive antenna could be used on the spacecraft. The frequency would not necessarily be in the Ka band.

Note that if the Teledesic services become available, the implementation of the backhaul links and the high-speed Internet would be greatly simplified. Nevertheless, there might be the RF interference problem between the Teledesic system and the direct downlink as they would operate at the same Ka-band frequencies (see below).

Ka-band Frequency Selection and Filing

Selection of suitable Ka-Band frequencies for the NASA direct link should be studied with respect to susceptibility to interference and equipment compatibility with NASA/ TDRSS-H, I, and J RF equipment and commercial RF equipment. FCC/NTIA and ITU filings for the selected Ka-Band frequencies should then follow.

Figure 5.4-3 summarizes the Ka-band frequency allocation to different services and orbits, according to the ITU. The NASA Ka-Band direct links may be qualified for the 500-MHz MSS/NGSO (mobile satellite services/non-geostationary orbit) band (uplink: 28.6–29.1 GHz and downlink: 18.8–19.3 GHz) that is shared with the Teledesic system.
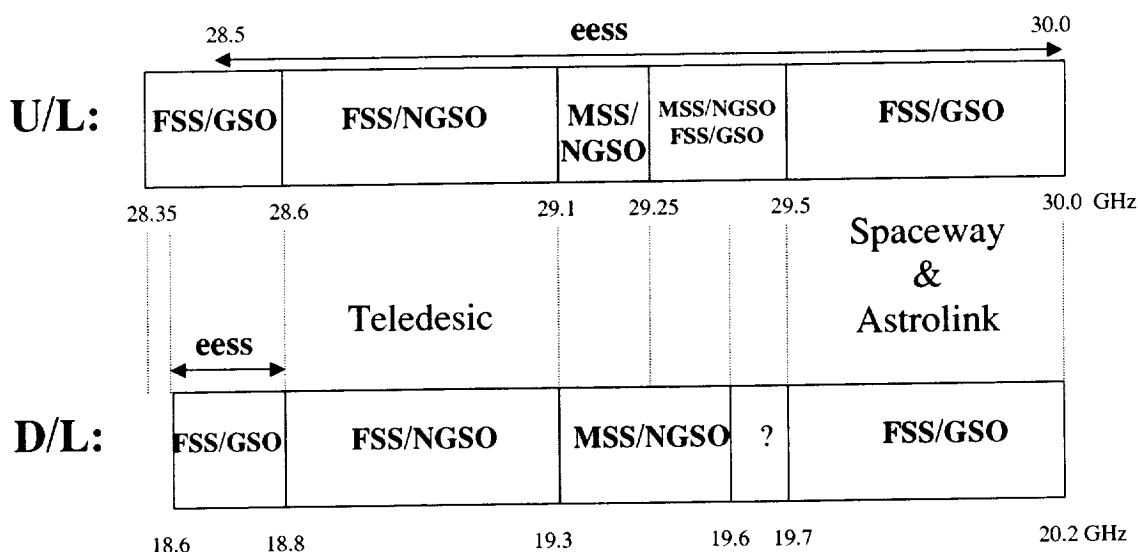
Figure 5.4-3 Ka-Band ITU Allocation

The NASA Ka-Band direct link may also be qualified for the EESS (earth exploration satellite services) band, shown in Figure 5.4-3. As far as priority is concerned, EESS is secondary to other services shown in the figure. A suitable selection may be a 100-MHz band from 28.5 to 28.6 GHz for uplink and a 200-MHz band from 18.6 to 18.8 GHz for downlink.

From general interference considerations, sharing with the FSS/NGSO (e.g., Teledesic), as opposed to sharing with the FSS/GSO (e.g., Spaceway), will result in more interference, and the coordination will be more difficult.

NASA should also consider using the same Ka-Band frequencies that the TDRSS-H, I, and J satellites will operate on (the ISL return link: 25.25 to 27.50 GHz and ISL forward link: 22.55 to 23.55 GHz) if it is acceptable to FCC/NTIA and ITU. It will be simpler to share with GSO satellites and to perform coordination within NASA.

Teledesic is not likely to be deployed within the next several years. Accordingly, the FSS/NGSO Ka-band should be treated as the primary candidate. Note also that if Teledesic or Teledesic-like systems were deployed, one could still implement the SC1 by placing SC1 earth stations in unpopulated areas where Teledesic does not have any customers other than the backhaul links associated with the SC1 earth stations; therefore, coordination would be straightforward.

Link Budget and Cost Tradeoff Analyses

Link budget and cost tradeoff analyses should be performed to determine the optimal number of earth stations required, optimal sizing for the earth station and spacecraft antennas, and the HPA needed to support individual and aggregated NASA missions. Work on standardization of the earth stations and of spacecraft RF equipment should also be carried out.

Protocol Issues

The protocol issues that must be resolved are those discussed in Section 4.5. These include the route propagation issue for a mobile network and the error rate problem.

5.5 Case 4. Ka-Band Space Relay Network

5.5.1 System Concept

Case 4 addresses relay links for command, telemetry, and communication between a LEO mission spacecraft and ground via commercial Ka-band relay satellites. These relay links ideally require access to an ISL of a commercial FSS satellite system. This concept is similar to that to be offered by TDRSS-H, I, and J system.

Alternatively, these relay links can be served by an MSS Ka-band satellite system that has global coverage. They should operate as MSS because a LEO mission spacecraft is a mobile station according to ITU regulations. They also require global coverage because the main reason for using relay links rather than direct links is to have real-time or near real-time transmission.

The network architecture for the Case-4 system concept is shown in Figure 5.5-1.
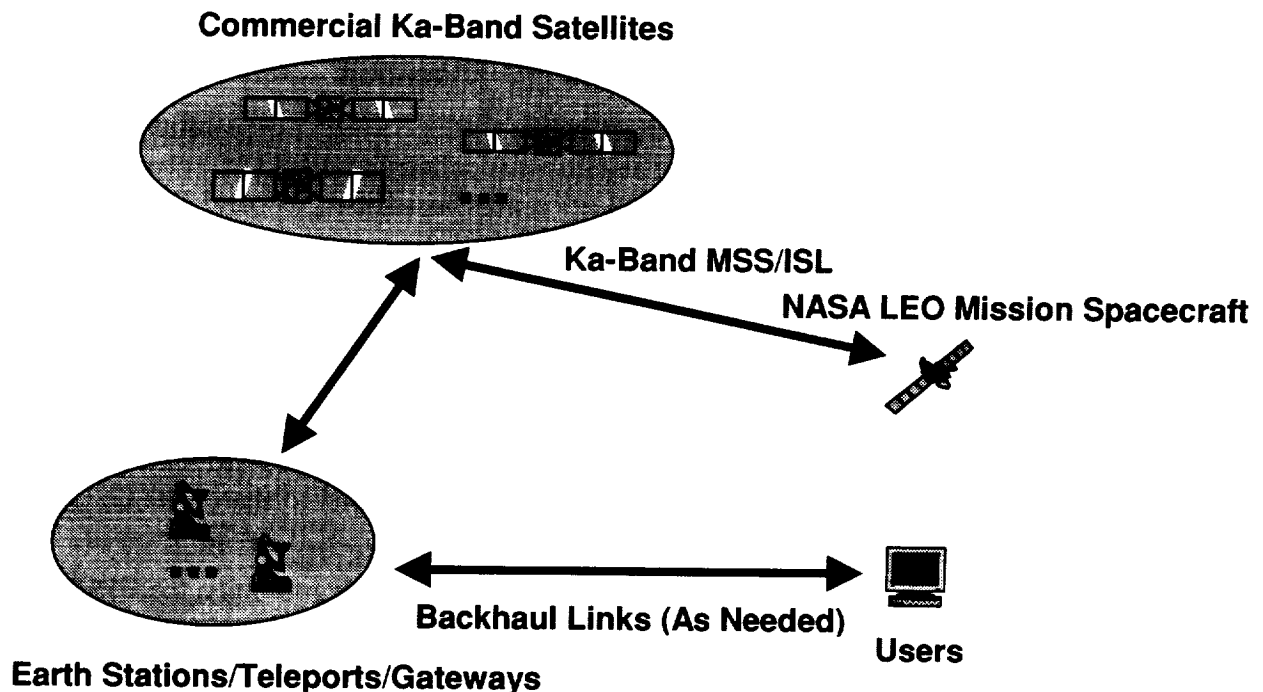

Commercial Ka-Band Satellites

Ka-Band MSS/ISL

NASA LEO Mission Spacecraft

Backhaul Links (As Needed)

Users

Earth Stations/Teleports/Gateways

Figure 5.5-1 Network Architecture for Case 4 System Concepts

5.5.2 Technical and Technology Gaps

There are three commercial satellite systems equipped with Ka-band ISLs: Iridium, Astrolink, and Teledesic. The operation of the Iridium system has been terminated, the development of the Teledesic system has been put on hold, and the Astrolink system is being developed for operation in 2003. Unlike the TDRS system, these ISLs are for internal routing within the satellite constellation. That is, they are not designed to communicate with a "user" spacecraft. Because of the limited market, there does not appear to be a commercial filing for a system to provide this kind of communication service in the near future, even though the cost of ISLs would go down significantly with the deployment of the commercial systems.

There do not appear to be filings now or in the foreseeable future for MSS Ka-band (LEO or GEO) systems with global coverage, probably because of the lack of a compelling business case.

Boeing has recently announced a space-based high speed Internet service for aircraft called Connexion [BOEI]. This service will initially serve North America and will gradually be extended to global coverage. It is not clear when global coverage will become available. Operating at frequencies other than Ka-band makes this system a less than ideal match to the IOA Plan.

Commercial Ka-band satellites that will soon be available are classified as FSS and are either equipped with onboard processing capability or are bent-pipe. The former include the GEO Astrolink satellites, GEO Spaceway satellites, and the LEO Teledesic satellites. The latter include GEO satellites from Intelsat, Telesat (Canada), Eutelsat, and others. These satellites are not suitable for establishing relay links between a LEO mission spacecraft and ground. As discussed earlier in Section 4.4, providing an MSS using an FSS segment is not compliant with the ITU rules and regulations. In the past, such non-compliances have sometimes been allowed on a non-interference basis. That is, if a complaint about harmful interference is filed, the non-compliant service must be stopped.

There are also other issues and problems associated with these commercial FSS Ka-band satellite systems. For the Teledesic satellite system, there are likely problems with satellite coverage and connection because the Teledesic satellites are also LEO and are used in a very well-coordinated fashion where the location of an earth station (called user equipment, UE) is assumed fixed. When a UE moves, the system would not know how to assign beams and satellites to the moving UE. The beam and satellite handoff algorithms onboard the Teledesic satellites and the Teledesic network operation center can be modified, but it would be extremely complex and costly because the modifications would have to be done on both the satellites and the earth stations, and it would defeat the purposes of the FSS category of service.

For the Astrolink or Spaceway satellite systems, there is also the coverage problem. Neither system provides global coverage. There is also a beam handoff problem, as each satellite has many uplink and downlink spot beams.

For bent-pipe satellites, space segment can be leased to tailor the requirements. However, it would be very costly. More importantly, these bent-pipe satellites are in GEO and do not have global coverage even when they are combined together.

Table 5.5-1 summarizes problems and issues associated with the Case 4 Ka-band space relay network. A research project (TRL 1) could be carried out to investigate concepts for modifying

the Ka-band systems mentioned (i.e., spot beams, onboard demodulation, onboard switching, and bandwidth-on-demand MC-TDMA) to serve fast moving user terminals.

Table 5.5-1 Issues and Problems Associated with the Case 4 Space Relay Network

Space Segment	Issues/Problems			
	MSS/ISL	Beam Coverage	Beam Connect/Handoff	Availability
ISL Iridium, Teledesic, Astrolink		X ?	X	
MSS		?	?	X
FSS/GSO/OBP Spaceway, Astrolink	X	X	X	
FSS/GSO/Bent-Pipe	X	X ?	X ?	
FSS/NGSO/OBP Teledesic	X	X ?	X ?	

5.6 Case 5. Optical Space Relay Network

Interest in optical technology for free-space communications may be spurred by recent system designs such as the French Artemis data relay satellite and Teledesic, both of which will utilize optical ISLs.

5.6.1 System Concept

This concept uses an optical return link to relay data from a LEO mission spacecraft to a GEO communications satellite. There is no atmospheric turbulence or attenuation in this link to degrade performance, so the advantages of optical wavelengths can be better realized. Note that there would still be performance impairments even without atmospheric degradation. The principle impairment is due to vibration in the spacecraft and instrument structures, which impacts fine beam pointing.

The forward link to the mission spacecraft might not be optical since the required bandwidth usually would be significantly lower. The design choice depends on the bandwidth, size, weight, and power trades.

The concept assumes that, as in Artemis, the link to ground is an RF link. This is a nearer-term solution than using optical frequencies on the space-ground link. The concept could be implemented near-term on an experimental basis using Artemis as the relay station. In the future, however, with optical links in the 10 Gbps range, an RF link to ground could be a potential bottleneck.

The main system components are:

- Mission Platform: Space-Qualified Optical Transceiver
- Relay Satellite: Space-Qualified Optical Transceiver

- Earth Station: Not unique to this case. Conventional RF earth station technology would be used.

Advantages of Optical

According to JPL, the theoretical advantage of optical over X band is 72 dB [JPL1]. This margin can be used by the system designer to reduce size, weight, and power, while at the same time increasing data rate. The example given in the referenced web page is a reduction to one-half of the weight, one-half of the power, one-tenth of the volume, one-tenth of the collecting area, and 10-100 times the data rate.

Another advantage is that since the optical spectrum is unregulated, no licenses are required. Also, the narrow beam width allows for a high efficiency of spectrum reuse.

A final advantage to be mentioned is that commercial fiber optics technology can be used in these free-space systems. Examples of components that can be used include solid state lasers, erbium-doped fiber amplifiers, modulators, and wavelength division multiplexing devices.

Disadvantages of Optical

An optical system will have a significantly reduced beam diameter compared to RF. In the case of JPL's Optical Communications Demonstrator (OCD), the beamwidth is 10 microradians (0.0006 degree). The requirement for pointing and tracking such a narrow beam is one of the main technological challenges in such a system. Vibration must be controlled within the instrument, and to some extent within the whole spacecraft, depending on the degree of isolation from the main spacecraft body. Thus the entire spacecraft must be designed with thermal, mechanical, and attitude stabilization characteristics driven by the optical transceiver requirements.

5.6.2 Current Technology

The discussion of current technology will be limited to complete integrated optical transceiver units that have been recently developed or are under development. They are:

- Semiconductor Intersatellite Link Experiment (SILEX)
- Laser Utilizing Communications Experiment (LUCE)
- Small Optical User Terminal (SOUT)
- Small Optical Telecommunications Terminal (SOTT)
- Short Range Optical Intersatellite Link (SROIL)
- Solid State Laser Communications in Space (SOLACOS)
- Astrolink 1000

The characteristics of these systems are listed in Table 5.7-1.

Table 5.7-1 Optical Intersatellite Link Experiments

Experiment	Units	SILEX	LUCE	SOUT	SOTT	SROIL	SOLACOS	Astrolink 1000
TRL		8	8	5–6	1	NA	4?	8
Telescope aperture	cm	25	26	7	20	4	15	NA
Data rate	Mbps	50	50	2	1000	1200	650	1240
Wavelength	microns	0.847	0.85	0.847	NA	NA	1.6	NA
Laser output	mW	120	200	NA	NA	NA	1000	NA
Laser type		diode	diode	AlGaAs	NA	NA	Nd:YAG	NA
Range	km	45,000	LEO-GEO	LEO-GEO	83,000	6,000	NA	1,600
Weight	kg	157	100	25	47	15	70	14
Manufacturer (country)		Matra Marconi (France)	(Japan)	Matra Marconi (UK)	Matra Marconi (UK)	Oerlikon-Contraves (Germany)	Dornier (Germany)	Astroterra (US)
Contracting Agency		ESA	NASDA	ESA	NA	ESA	German government	BMDO

Sources: [WTEC], [ESA], [WALL]
NA – Not available

Notes

1. SILEX: The flight models for both the LEO mission spacecraft, SPOT 4, and the GEO relay satellite, Artemis, have been developed.

2. LUCE: This is a Japanese-developed terminal that is compatible with SILEX on Artemis and will be carried on board the Optical Interorbit Communications Engineering Test Satellite (OICETS).

3. SOUT: A much smaller SILEX-compatible terminal was designed by Matra Marconi. This project was limited to the production of a technology demonstrator. As well as reducing the weight significantly, it incorporated an advanced vibration damping mount that reduced the bandwidth of the fine-pointing system to the extent that a CCD could perform both acquisition and tracking.

4. SOTT: This is a modified version of SOUT, intended to boost the data rate to 1 Gbps. It is targeted at commercial applications such as GEO-GEO links (83,000 km) for Hughes Spaceway. It is currently under development.

5.6.3 Technology Projection

The technology of optical ISLs is currently in an experimental phase, although the underlying technologies appear to be mature. Optical ISLs have been given renewed impetus by the market that may be created by new commercial LEO architectures such as Teledesic. The large number of units required by Teledesic would significantly drive down the cost of this technology. The technology will remain in the realm of one-of-a-kind and custom built systems unless the new commercial systems are carried forward. However, even without the commercial systems, the technology can be expected to continue to advance, driven by, for example, military needs.

From the examples above, it appears that the current state of the art is represented by SOTT. In other words, a reasonable specification today might be a 1 Gbps data rate, a LEO-to-GEO range, in a 25 kg package with an aperture of a few inches. Currently, Ka-band systems with data rates in the neighborhood of 1 Gbps are also planned. The next step for optical systems would seem to

be a data rate of 10 Gbps, which is more in line with terrestrial fiber technology, and would offer a clear advantage over RF. A reduction in weight to 10 kg would appear to be more compatible with the trend toward microsatellites (less than 100 kg). The Communications Research Laboratory of Japan has a plan to achieve a flight-worthy system performing at 10 Gbps by 2010 [WTEC]. It is assumed that other agencies such as the U.S. military, with its greater resources, could achieve this goal much sooner.

Transmission through the Atmosphere

Transmission through the atmosphere is a logical extension of optical technology. While the technology for optical ISLs appears to be in hand, optical transmission through the atmosphere is a much greater challenge.

One obvious problem is cloud cover, which is mostly opaque to optical wavelengths. The standard solution is geographic diversity, a set of geographically dispersed ground stations in low cloud-cover locations in sufficient numbers that the availability requirement is met. Low cloud-cover locations may include mountaintop observatories, which is the approach used in the SILEX experiment. Looking to the future, long endurance upper atmospheric air vehicles might also be good platforms.

Sites high in the atmosphere have the additional advantage that the path through the atmosphere is reduced and traverses lower density air. This helps with the problem of pulse spreading. Pulse spreading occurs when the optical energy from a short pulse scatters off of air molecules and arrives at the detector delayed with respect to the direct path. This pulse spreading is a limiting factor on data rate. At data rates of 1 Gbps, pulse spreading will definitely be a problem [GAGL].

Other problems are caused by refraction of the beam as it passes through atmospheric turbulence. This causes distortion of the beam wavefront, beam breakup, and wander of the beam. The effects are somewhat different on the uplink and downlink beams.

Refraction and scattering together cause beam decoherence. This is a problem for heterodyne detection systems since, in these systems, phase coherence across the beam is required to allow efficient mixing with the optical local oscillator.

The time scale of these effects differs greatly. Atmospheric turbulence effects are slowly varying with respect to the information symbol period. Electro-mechanical actuators are fast enough to compensate for turbulence. This fact is the basis of current adaptive optical systems. Most of these systems are designed for astronomical sources (plane wavefronts) where beam wander is not a problem. However, in the field of ballistic missile defense, the problem of adaptive optics for laser beams has been the subject of research for many years. The U.S. Air Force's Airborne Laser antimissile system uses an adaptive optical system designed for restoring and maintaining a laser's beam shape and position at the target.

Another approach for dealing with turbulence is burst transmission, where the burst is short compared to the rate of change of the turbulence.

Some current experiments in through-the-atmosphere optical communications are mentioned below.

The Optical Communications Demonstrator (OCD) experiment is being done by JPL [JEGA]. It uses a 10 cm telescope with a goal of up to gigabits per second performance. It is being used for laboratory and open-air field tests. The JPL website [JPL1] lists the project at TRL 7. A demonstration from a spaceborne platform is scheduled for 2002.

SILEX, described above, will be used for space-to-ground tests using a 1 meter ground telescope at an observatory at an elevation of 11,000 feet in the Canary Islands.

Astrolink 1000, described above, will also be involved in space-to-ground experiments.

Geolite is an experiment sponsored by the National Reconnaissance Office. There is not much information available on its specifications.

Other Concepts

NASA centers have proposed several innovative concepts in the optical field. One is the modulated retroreflector [MONF]. A forward link consists of a laser transmitting to a receiver. At the receive station, a retroreflector reflects the beam back to the source. The characteristic of a retroreflector is that it always reflects back to the source, regardless of the relative position or motion of the source. This retroreflector has a polarization modulator that allows a signal to be imposed on the reflected beam. No laser source is required for the return link. This scheme has obvious advantages for space communications, where the size, weight, and power budgets may differ greatly at the two ends of the link, especially if one terminal is on the ground.

Another concept, from JPL, is to use the optical telescope on the spacecraft for more than one purpose [HEMM]. For example, the telescope could be used for star tracking as well as communications. Or, an earth imaging telescope could be used for communications.

5.6.4 Technical and Technology Gaps

At the component level, there appear to be no technology shortfalls for optical to be competitive with RF in the ISL application.

ESA's SILEX experiment has been developed up to at least TRL 8. However, the technology is rather outdated, and the terminal unit is too heavy to be competitive with RF technology.

A small, lightweight intersatellite link terminal such as SOTT is a more realistic means to implement the optical relay concept. It appears that SOTT is in the prototype stage, so additional funding would be needed to carry it to the flight-qualified stage. SOTT appears to be compatible with SILEX, so a relay platform is available near-term for experiments. NASA's OCD appears to have very similar specifications and may be closer to flight qualification. However, it is not designed to interface to SILEX. Even though it was designed for a through-the-atmosphere link, there is no reason that it could not be used for an ISL.

5.7 Other Concepts Not Investigated

Hybrid Architectures

We did not examine hybrid architectures, even though the asymmetric nature of the data traffic load naturally suggests a hybrid approach. A hybrid architecture would consist of the use of two different networks: one for the forward link and another for the return link.

High Altitude (Stratospheric) Platforms for Communications Relay

A high altitude platform has the potential to provide a longer contact time with a spacecraft owing to a lower angle to the horizon, reduced atmospheric absorption, and reduced weather-related impairments. Such a platform would also have potentially more data storage capacity than a small spacecraft.

Direct interface to Terrestrial Wireless Networks

At least one investigator is pursuing the concept of using cellular technology to communicate between a LEO microsat (3 Corner Sat) and the ground [HORA].

6. RECOMMENDATIONS

We have examined five example architectures for an IP-based commercial space communications network for NASA airborne, LEO, and MEO mission platforms in accordance with the policies described in the IOA Baseline [CSOC]. In some cases we used actual commercially available services and in others projected future services and technology to construct these architectures. We assessed technological issues that need to be addressed within the context of these example architectures. We emphasize only those technologies that are unique to the IOA concept. Below we make general recommendations and recommendations on specific technology and technical issues that NASA should pursue in support of the IOA. The recommendations are grouped according to the associated architecture.

6.1 General

6.1.1 Systems Engineering

We find that the technologies and technical issues that merit investment of resources by NASA depend greatly on the network architecture to be selected. For example, the protocol issues differ in the space relay architecture and the direct architecture because of the differing propagation delay. Similarly, the EIRP requirements, a major technology and engineering driver, differ in the two approaches. We therefore recommend that NASA conduct a systems engineering effort aimed at selecting a specific system concept and a more detailed architecture description in order to prioritize the technology and development efforts.

The systems engineering process is the recommended means to prioritize among the many potential developmental activities. Accordingly, we recommend that the process be carried out at least down to the level of architecture definition, as outlined below:

- Develop LEO/MEO mission communications requirements sets (1 or more)
- Develop IOA LEO/MEO mission concept of operations
- Develop IOA LEO/MEO mission space network architectures
  - Perform trade analyses
  - Perform link budget analyses at candidate frequency bands
  - Select frequency bands

6.1.2 Protocols

Part of the systems engineering effort is protocol selection. Some of the key tasks that need to be performed are:

- Select/develop a route propagation protocol for a LEO/MEO mobile network environment
- Select/develop a solution for a TCP/IP high error rate space channel
- Select/develop a solution for TCP in a high delay-bandwidth product channel
- Simulate use of IP, TCP, and UDP in a LEO/MEO network architecture

- Develop "middleware" architecture for handover and connectivity in a LEO/MEO network

- Develop a demand access space-ground link protocol

- Evaluate and select encryption and key-distribution protocols

6.1.3 Storage Technology

Storage technology can have a great impact on the network architecture. We recommend that NASA evaluate some of the newer approaches to storage, such as the Nanochip product, and incorporate these in the system tradeoff studies.

6.1.4 Baseband Processing

Some of the network processing functions that are unique to the IOA are listed below. These functions need to be incorporated in a space-qualified processor for the mission spacecraft:

- "Middleware" layer: Connectivity scheduler protocol

- TCP/UDP layer: A protocol gateway such as the Mentat Sky-X product

- IP layer: Routing, route propagation for mobile nodes, network management, router access security, and IP-based security

- Link layer: Demand assignment link access protocol

- RF layer: NASA should take advantage of the low-cost, high data rate modem and codec technology that will be available when Spaceway and Astrolink are deployed

6.2 L-Band Global Network for Airborne Platforms

We expect that high altitude atmospheric platforms will play a greater role in the future. The Inmarsat Aero services appear to be well-suited to this type of mission. We therefore recommend that NASA pursue a program to qualify a commercial Inmarsat Aero transceiver for the high altitude environment for high altitude balloons and long-endurance aircraft.

6.3 L-Band Global Network for LEO Platforms

We recommend that NASA accelerate development of the SHUCS space-qualified Inmarsat Aero transceiver through partnership with Spacehab. We believe that this concept could serve as a prototype for more advanced, high-bandwidth networks, as well as serving low data rate missions in the IOA Transition Term.

6.4 Ka-Band Direct-to-Ground Network

We recommend that NASA pursue one of the two concepts (SC1 or SC2) under this heading. Alternatively, SC1 could be pursued with SC2 as a phased enhancement to it. We expect that the cost of either approach will be at least one or two orders of magnitude less than the cost of the TDRSS H, I, J series. "Air-time" charges would be proportionally less as well, assuming a contract-for-service model.

For the LEO-teleport concept, the approach would be for NASA to contract with one of the commercial providers for Ka-band service on the downlink and S, X, or Ka band on the uplink.

This would probably require some minimum financial commitment by NASA in order for the commercial provider to be willing to invest in an upgrade of the infrastructure to Ka band. We expect that NASA could obtain Ka-band service at a significant discount compared to building its own infrastructure since it is expected that the service provider will absorb much of the up-front cost.

For the miniature, low-cost terminal approach, we recommend that NASA evaluate the Spaceway and Astrolink low-cost terminal technology. The terminals must be modified for tracking LEO spacecraft.

For both concepts, a spacecraft transceiver is needed. A Ka-band transmitter, possibly a Ka-band receiver, and a tracking antenna system are needed. It is recommended that NASA modify, as needed, the phased array antennas that it has already developed for this purpose.

For both concepts, we recommend that NASA pursue the development of a high capacity recorder based on COTS technology as a way to mitigate coverage gaps that will occur in a direct-to-ground architecture.

NASA should pursue interference analyses against Ka-band GSO systems (e.g., TDRSS, Spaceway, Astrolink, and future commercial Ka-band bent-pipe satellites) and Ka-band NGSO systems (e.g., Teledesic). Then, NASA should secure frequencies for Ka-Band direct-to-ground links by filing with the ITU and FCC/NTIA. These three frequency sets are recommended for filing consideration:

- The Ka-band that NASA is using for the TDRSS system: Uplink (25.25–27.50 GHz) and downlink (22.55–23.55 GHz)

- The Ka-band allocated for MSS/NGSO: Uplink (28.6–29.1 GHz) and downlink (18.8–19.3 GHz)

- The Ka-band allocated for EESS: Uplink (28.5–28.6 GHz) and downlink (18.6–18.8 GHz)

6.5 Ka-Band Space Relay Network

We recommend that NASA conduct studies on techniques for interfacing with future generation spot-beam GEO satellites. These techniques should depend on the satellite payload architectures: how the uplink beams are connected to the downlink beams and how uplink signals are processed by the satellite payload. These techniques should be tested with future experimental/research satellites.

6.6 Optical Space Relay Network

We recommend that NASA extend its research and development activities in optical communications to include LEO/MEO space relay communications as well as deep-space communications.

To that end, one possibility is to fund a space-relay experiment using JPL's OCD terminal interoperating with Artemis. This would involve adapting the OCD optical transceiver for interoperation with Artemis and upgrading to space qualification.

Longer term, the next step in technology would be the development of a 10-Gbps, 10 kg optical ISL terminal. This could be carried piggyback on a commercial GEO communications satellite that has ISL interfaces.

Associated with these activities, it would be beneficial to investigate the use of optical fiber technology for free-space application and the use of adaptive optics technology for the problem of through-the-atmosphere optical communications.

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LIST OF ABBREVIATIONS

ACE	Advanced Composition Explorer
AES	Advanced Encryption Standard
AOR-E	Atlantic Ocean Region-East
AOR-W	Atlantic Ocean Region-West
APL	Applied Physics Laboratory
AS	Autonomous system
ATM	Asynchronous Transfer Mode
BGP	Border Gateway Protocol
BMDO	Ballistic Missile Defense Organization
BPSK	Binary phase shift keying
BSS	Broadcast Satellite Service
CDMA	Code division multiple access
CMC	Comsat Mobile Communications
COTS	Commercial off the shelf
CSOC	Consolidated Space Operations Contract
CW	Continuous wave
D3	Direct Data Distribution
DBS	Direct broadcast satellite
DES	Data Encryption Standard
D/L	Downlink
DNS	Domain Name Service
DRS	Data Relay Satellite
DRTS	Data Relay and Tracking Satellite
DSL	Digital subscriber line
DSP	Digital signal processor
DTMF	Dual tone multiple frequency
EESS	Earth exploration satellite service
EIRP	Equivalent isotropic radiated power
EOS	Earth Observing System
ESA	European Space Agency
ETS	Engineering Test Satellite
EUVE	Extreme Ultraviolet Explorer
FCC	Federal Communications Commission
FEC	Forward error correction
FRA	Ferroelectric Ka-band reflectarray antenna
FSS	Fixed Satellite Service
FTP	File Transfer Protocol

GEO	Geosynchronous or geostationary earth orbit
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GRGT	Guam Remote Ground Terminal
GRO	Gamma Ray Observatory
GSFC	Goddard Space Flight Center
GSM	Global System for Mobile (Communications)
GSO	Geostationary orbit
HCI	Hughes Communication Inc.
HEMT	High electron mobility transistor
HPA	High power amplifier
IOA	Integrated Operations Architecture
IOR	Indian Ocean Region
IP	Internet Protocol
IPSec/ESP	Secure IP/encapsulated security payload
ISDN	Integrated services digital network
ISL	Inter-satellite link
ISP	Internet service provider
ISS	Inter-satellite service; also International Space Station
ITU	International Telecommunications Union
JPL	Jet Propulsion Laboratory
KSA	K-Band Single Access
LDBP	Long Duration Balloon Programs
LEO	Low earth orbit
LES	Land earth station
LNA	Low noise amplifier
LUCE	Laser Utilizing Communications Experiment
MA	Multiple access
MAGS	Miniature autonomous ground station
MCM	Multiple carrier modulation
MC-TDMA	Multiple-carrier time division multiple access
MEMA	Microelectro-mechanical actuators
MEO	Medium earth orbit
MIPS	Million instructions per second
MMIC	Monolithic microwave integrated circuit
MSS	Mobile Satellite Service
NASDA	Japanese National Space Development Agency
NAT	Network Address Translation
NCC	Network Control Center
NGSO	Non-geostationary orbit

NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NODC	Network Operation and Data Distribution Center
NSA	National Security Agency
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
OCD	Optical Communications Demonstrator
OFDM	Orthogonal frequency division multiplexing
OICETS	Optical Interorbit Communications Engineering Test Satellite
OSPF	Open Shortest Path First
PCS	Personal communication system
pHEMT	Pseudomorphic high electron mobility transistor
PLMN	Public land mobile network
POR	Pacific Ocean Region
PSTN	Public switched telephone network
QAM	Quadrature amplitude modulation
QoS	Quality of Service
QPSK	Quadrature phase shift keying
RASCL	Remote Satellite Communication Link
RDSS	Radio-determination satellite service
RF	Radio frequency
RIP	Routing Information Protocol
RTT	Round trip time
SA	Single access
SAR	Synthetic aperture radar
SC	System Concept
SCTDB	Satellite Communications Technology Database
SDARS	Satellite digital audio radio services
SHUCS	Spacehab Universal Communications System
SILEX	Semiconductor Intersatellite Link Experiment
SNIP	Satellite Network Interoperability Panel
SNOE	Student Nitric Oxide Experiment
SOLACOS	Solid State Laser Communications in Space
SOS	Satellite operations service
SOTT	Small Optical Telecommunications Terminal
SOUT	Small Optical User Terminal
SROIL	Short Range Optical Intersatellite Link
SRS	Satellite research service
SSA	S-Band Single Access
SSPA	Solid state power amplifier

STARLINK	Satellite and Return Link
STS	Space Transportation System
TAGS	Transportable Autonomous Ground Station
TCC	Turbo Convolutional Coding
TCP	Transmission Control Protocol
TDMA	Time division multiple access
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TPC	Turbo Product Coding
TRL	Technology readiness level
TWTA	Traveling wave tube amplifier
UAV	Unmanned aerial vehicle
UDP	User Datagram Protocol
UE	User equipment
UHF	Ultra high frequency
U/L	Uplink
USN	Universal Space Network
VHF	Very high frequency
VSAT	Very small aperture terminal
WSC	White Sands Complex
WTEC	World Technology Evaluation Center
ZOE	Zone of Exclusion

APPENDIX A. INCLUDED NASA MISSIONS

Mission Name	Mission Family (Program)	Launch Date (Month-Year)	Plan and Goal Life (Years)
IMP-8	N/A	Oct-73	27 and 27
ERBS	N/A	Oct-84	16 and 16
HST	Origins	Apr-90	15 and 15
ULYSSES	N/A	Oct-90	11 and 11
UARS	N/A	Sep-91	12 and 12
SAMPEX (SMEX-1)	Explorers	Jul-92	6 and 6+3
ASCA	N/A	Feb-93	7 and 7
GOES-J	NOAA	May-95	5 and 5
RXTE	N/A	Dec-95	5 and 5+3
NEAR	N/A	Feb-96	4 and 4
FAST (SMEX-2)	Explorers	Aug-96	2 and 2
Mars Global Surveyor	N/A	Nov-96	5 and 5
GOES-K	NOAA	Apr-97	5 and 5
ORBVIEW-2	N/A	Aug-97	10 and 10
ACE	Explorers	Aug-97	2 and 5
VOYAGER 1	N/A	Aug-97	42 and 42
VOYAGER 2	N/A	Sep-97	42 and 42
CASSINI	N/A	Oct-97	11 and 11
TRMM	EOC	Nov-97	3 and Indef
TRACE (SMEX-4)	Explorers	Apr-98	1 and >1
SWAS (SMEX-3)	Explorers	Dec-98	2 and 2
STARDUST	Discovery	Feb-99	7 and 7
WIRE (SMEX-5)	Explorers/Origins	Mar-99	4 mos and 4 mos
LANDSAT-7	EOS	Apr-99	6 and 6
GOES-L	NOAA	Dec-98	5 and 5
FUSE (MIDEX)	Explorers/Origins	Mar-99	3 and 3
QuikSCAT	EOS/ESSP	Apr-99	2 and 3
Chandra XRO	N/A	May-99	5 and 7
TERRA	EOS	Jun-99	5 and 6
EO-1	NMP	May-99	unk and unk
IMAGE (MIDEX-1)	Explorers	Feb-00	2 and 2
TIMED	N/A	May-00	2 and 2
JASON	EOS	May-00	5 and 5
HESSI (SMEX)	Explorers	Jul-00	3 and 3
VCL	ESSP	Aug-00	2 and 2

Mission Name	Mission Family (Program)	Launch Date (Month-Year)	Plan and Goal Life (Years)
GP-B	N/A	Oct-00	1.5 and 1.5
MAP (MIDEX-2)	Explorers	Nov-00	15 mos and 3 years
Triana	N/A	Dec-00	3 and 5
ADEOS-II	EOS	Dec-00	3 and 3
PM-1	EOS	Dec-00	6 and 6
GRACE	ESSP	Jun-01	5 and 5
GOES-M	NOAA	Jul-01	5 and 5
ICESat (LAM-1)	EOS	Jul-01	3 and 5
SIRTF	Origins	Dec-01	2.5 and 5
SORCE	EOS/ESSP	Jul-02	6 and 6
CHEM-1	EOS	Dec-02	5 and 6
ST-3	Origins	Jun-03	1 and 2
SIM	Origins	Jun-05	5 and 5
NGST	Origins	Jun-07	5 and 10
CHEM-II	Origins	Dec-08	5 and 6
TPF	Origins	Jun-11	6 and 6
ISS	HEDS	Nov-98	20 and 20
STS	HEDS	various	

APPENDIX B. ACQUISITION TIME CALCULATION

The two parameters that directly affect the acquisition time are antenna gain (g) and C/No-g in dB or EIRP less path loss. (E)

The S/N (Ct/No) must be about 15 dB or 32.

$$\frac{C}{No} = \frac{EIRP \cdot K}{PL \cdot Temp} \cdot g = k \cdot g \qquad \text{where } k = \frac{EIRP \cdot K}{PL \cdot Temp}$$

$$\frac{C \cdot t}{No} = k \cdot g \cdot t \qquad \text{where t is the time to detect}$$

$$\text{thus } t = \frac{32}{(k \cdot g)} \qquad \text{for each beam position}$$

If the beams were perfect cones, we would need g/2 of them to cover a hemisphere, but we can reasonably assume that they could be spaced at 1/3 of this, or that we need 3/2 g beams. The hemisphere has 2π square radians, thus the beam covers about $4 \cdot \dfrac{\pi}{3 \cdot g}$ square radians. The radius would be $\dfrac{1}{3} \cdot \dfrac{\sqrt{6}}{\sqrt{g}}$. There would be $\pi \cdot \sqrt{6} \cdot \sqrt{g}$ beams around the horizon. At any angle, ϕ, from the start of a concentric circle scan, there would be $\pi \cdot \sqrt{6} \cdot \sqrt{g} \cdot \sin(\phi)$ beams, and it would take $32 \cdot \pi \cdot \dfrac{\sqrt{6}}{\sqrt{g}} \cdot \dfrac{\sin(\phi)}{k}$ seconds to perform the scan. If the roll rate of the platform or the drift rate of the communications satellite is r radians per second, we can only increase ϕ by two radii less rt per scan.

$$\Delta\phi = \left[2 \cdot \left(\frac{1}{3} \cdot \frac{\sqrt{6}}{\sqrt{g}} \right) - \left(32 \cdot \pi \cdot \frac{\sqrt{6}}{\sqrt{g}} \cdot \frac{\sin(\phi)}{k} \right) \cdot r \right] = \frac{2}{3} \cdot \sqrt{6} \cdot \frac{(k - 48 \cdot \pi \cdot \sin(\phi) \cdot r)}{\left(\sqrt{g} \cdot k\right)}$$

Acquisition Time Calculations

Frequency (GHz)	1.5	1.5	20
Antenna Gain (dB)	20	20	43
EIRP (dBW)	21	12.8	35.8
Roll (deg/sec)	5	2	2
Doppler (KHz ±)	30	30	600
Acquisition time (sec)	0.46	43.6	1.63

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13. ABSTRACT (Maximum 200 words)

As part of NASA's Integrated Operations Architecture (IOA) Baseline, NASA will consolidate all communications operations, including ground-based, near-earth, and deep-space communications, into a single integrated network. This network will make maximum use of commercial equipment, services and standards. It will be an Internet Protocol (IP) based network. This study supports technology development planning for the IOA. The technical problems that may arise when LEO mission spacecraft interoperate with commercial satellite services were investigated. Commercial technology and services that could support the IOA were surveyed, and gaps in the capability of existing technology and techniques were identified. Recommendations were made on which gaps should be closed by means of NASA research and development funding. Several findings emerged from the interoperability assessment: in the NASA mission set, there is a preponderance of small, inexpensive, low data rate science missions; proposed commercial satellite communications services could potentially provide TDRSS-like data relay functions; and, IP and related protocols, such as TCP, require augmentation to operate in the mobile networking environment required by the space-to-ground portion of the IOA. Five case studies were performed in the technology assessment. Each case represented a realistic implementation of the near-earth portion of the IOA. The cases included the use of frequencies at L-band, Ka-band and the optical spectrum. The cases also represented both space relay architectures and direct-to-ground architectures. Some of the main recommendations resulting from the case studies are: select an architecture for the LEO/MEO communications network; pursue the development of a Ka-band space-qualified transmitter (and possibly a receiver), and a low-cost Ka-band ground terminal for a direct-to-ground network; pursue the development of an Inmarsat (L-band) space-qualified transceiver to implement a global, low data rate network for LEO/MEO mission spacecraft; and, pursue developmental research for a miniaturized, high data rate optical transceiver.

14. SUBJECT TERMS

Communications satellites; Commercial satellites; Broadband satellite services; Integrated operations architecture; IOA; IOA intranet; Internet in the sky; NASA mission set; TCP/IP over satellite; Ka-band; Tracking and data relay satellite; TDRSS; Inmarsat; Ground stations; Space communications; Internet

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